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A three-dimensional kinematic analysis of Alpine skiing in moguls

Anton N. Arndt
University of Wollongong

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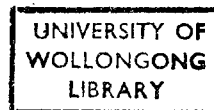
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**A THREE-DIMENSIONAL KINEMATIC ANALYSIS OF
ALPINE SKIING IN MOGULS**

A thesis submitted in partial fulfilment of the
requirements for the award of the degree of

HONOURS MASTER OF SCIENCE

from



THE UNIVERSITY OF WOLLONGONG

by

ANTON N. ARNDT, BSc.

DEPARTMENT OF HUMAN MOVEMENT SCIENCE

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ABSTRACT

The alpine skiing freestyle discipline of mogul skiing received full medal status at the 1992 Winter Olympic Games, resulting in a demand for expert coaching which would benefit from a detailed kinematic analysis. General alpine skiing injury mechanisms and the epidemiology thereof are well documented in scientific literature, however no studies have been conducted on injury mechanisms occurring specifically in mogul skiing. The dynamic nature of mogul skiing, in which impacts of the lower limb with moguls up to 1.5 m high occur at a high frequency, places considerable stress on the joints of the lower limbs. Personal correspondence with a number of mogul skiing World Cup competitors indicated a high proportion of elite competitive mogul skiers suffering from injuries at the knee joint. This study was an initial attempt at providing a detailed kinematic analysis of mogul skiing to be of technical assistance for coaching purposes and also to identify potential injury mechanisms encountered in this sport.

Three elite competitive mogul skiers skied a set course of moguls with the turn executed on the final mogul being filmed for subsequent analysis. Data was collected by two LOCAM high-speed cameras operating at a nominal frame rate of 200 Hz. The Direct Linear Transformation (DLT) technique was used to obtain the x, y and z coordinates of the markers positioned on the subjects. These were combined with manually obtained transformation measurements of the distances of these markers from previously defined local coordinate systems as input to the Motion Analysis Corporation (MAC) software package; KinTrak. This then defined the position of the subjects' segments in three-dimensions. Rotations of these segments about Joint Coordinate System (JCS) axes then permitted the calculation of angles of rotation of flexion/extension, abduction/adduction and internal/external rotation about the ankle, knee and hip joints. The analysis was a descriptive analysis treating each subject as a case study.

Results showed that the subjects skied over the mogul with flexion/extension motions correlating with those described in the literature as most effective in terms of aesthetics and force absorption. The results are applicable for coaching purposes by using the idea of a 'template' of specific variables to be compared between skiers. Two postures associated with injury to the anterior cruciate ligament (ACL) of the knees were identified by a combination of variables in a number of trials. The most commonly described alpine skiing injury mechanism in the literature concerning the medial collateral ligament (MCL) was not identified in any of the trials in this study. It is recommended that specific variables relating to injury be examined in further studies and that the quantifiable benefits of kinematic analysis to competitive coaching be continued.

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CHAPTER 1

INTRODUCTION

Moguls or 'bumps' are mounds formed on a snow skifield that has not been groomed (snow surface preparation by machines) and has been subjected to continual skier traffic. Moguls vary in shape and size depending on the amount of skier traffic, the ability of the skiers and the steepness of the slope. They pose an additional hazard to inexperienced skiers as they are more difficult to negotiate and maintain control than when skiing a smooth, well groomed slope. It is this difficulty which makes moguls attractive to experienced skiers who view them as a challenge to extend their skiing ability. Skiing a mogul field at speed requires not only good balance, control, timing and fast reactions to negotiate each bump but also a complete repertoire of skiing skills necessary to remain under control despite the continually, rapidly changing terrain.

Mogul skiing is an integral part of free skiing as well as a competitive skiing discipline. It has recently become recognised under the broader umbrella of freestyle skiing which also includes the elements of aerials and ski ballet. A mogul skiing World Cup circuit of competitions has been in place since 1971. The widespread recognition of mogul skiing as an individual, competitive event has culminated in its inclusion as a medal event in the 1992 Winter Olympic Games in Albertville, France.

A competitive mogul run is generally 250 - 300 m long and takes a competitor between 10 and 20 seconds to complete. This run is comprised of up to 40 turns executed on the moguls which are between 100 and 150 cm high. These values are only an indication of the characteristics of such a course and will vary as a result of numerous factors such as the skill level of the competition and the space available on a skifield for the competition. The ability of the individual competitor will also influence the number of turns executed and the time taken to complete the course. Two moguls are usually especially constructed in a competitive course as 'air bumps' to provide the competitor with a ramp for the completion of aerial manoeuvres. Competitive mogul skiing is judged upon style, aerial manoeuvres, control, difficulty and speed; with the fastest competitor down the course not necessarily the eventual winner. There is a greater qualitative emphasis than in the more traditional alpine racing events (slalom, giant

slalom, super giant slalom, downhill and speed skiing) in which time is the only form of assessment.

1.1 Context of the Problem

The speed with which mogul skiers negotiate a course, and thus the velocity with which they strike each individual bump exposes them to injury potential. Correspondence with several mogul skiing competitors has indicated a high occurrence of knee ligament damage amongst elite mogul skiers. Two of these elite mogul skiers had themselves experienced severe ligament damage that required reconstructive surgery. Six more members of their training group (n=10) also had similar problems. There is increasing concern that the young age of elite mogul skiing competitors, with a number of elite competitors in Australia under 18 years, can lead to chronic, long-term knee problems.

The precise mechanism responsible for such injuries in mogul skiing has not previously been assessed. It is likely there are many varied mechanisms. A kinematic description of mogul skiing will help identify such possible mechanisms.

Increased publicity and especially its acceptance as a full medal event in the 1992 Winter Olympic Games has made mogul skiing increasingly popular in Australia. There is also a demand for closer analysis of the sport to specify possibilities for improvement of technique.

1.2 Significance of this Study

There is an identifiable injury potential in mogul skiing, but this has not been documented in the scientific literature. No three-dimensional kinematic analysis has been conducted on mogul skiing to date and this study is seen as the first step in the determination of the exact injury mechanisms. The results of this study will be of use to competitive mogul skiers both as indications of possible injury mechanisms and possibilities of improvement of technique.

1.3 The Research Aims

The primary aim of this study was the kinematic description of alpine skiing in moguls and this was to be obtained through the analysis of the following variables :

- 1) The degree of flexion/extension at the hip, knee and ankle joints.
- 2) The degree of internal/external rotation of the tibia in relation to the femur and the femur in relation to the torso.
- 3) The degree of abduction/adduction at the knee and hip joints.
- 4) The absolute angles of the ankle, knee and hip joints.

An underlying hypothesis of the study was that the Direct Linear Transformation (DLT) technique of providing three-dimensional coordinates could be combined with three-dimensional rotations about coordinate systems to provide a kinematic description of the motions of elite, competitive mogul skiers.

1.4 Limitations and Delimitations

1.4.1 Limitations

- 1) Any change in the proportions, position or hardness of the reference mogul between subjects was assumed to be negligible.
- 2) Any difference between subjects as a result of different ski equipment used was assumed to be negligible.
- 3) It was assumed all subjects skied all trials at maximum effort in terms of style and speed.

1.4.2 Delimitations

- 1) Only elite competitive mogul skiers with international rankings were analysed in this study.
- 2) All trials were conducted on a series of five artificial moguls simulating a competitive course.
- 3) The turn executed on the last of the moguls was considered representative of a subject's mogul skiing style and ability.
- 4) Standard cinematographic analysis and digitising procedures were used and errors inherent in the use of these procedures were assumed to be negligible.
- 5) External body markers were used to reconstruct the anatomical positions of the body segments.

1.5 Definitions

Terms are defined in the context of this study as follows :

1. Anatomical frame of reference of the left foot.

Orthogonal axes embedded in the segment such that positive y is the axis representing the long axis of the segment (see Figure 1.1 of Anatomical Frames of Reference; AFOR).

Positive y:

Origin: mid-point of line connecting the malleoli of tibia and fibula.

Direction: anterior. This axis is represented in this study by a line connecting the mid-point of the lateral and medial hinge centres of the ski boot with the most anterior point of the boot.

Positive x:

Vertical, downward perpendicular to positive y.

Positive z:

Right-hand mutually orthogonal to positive x and positive y

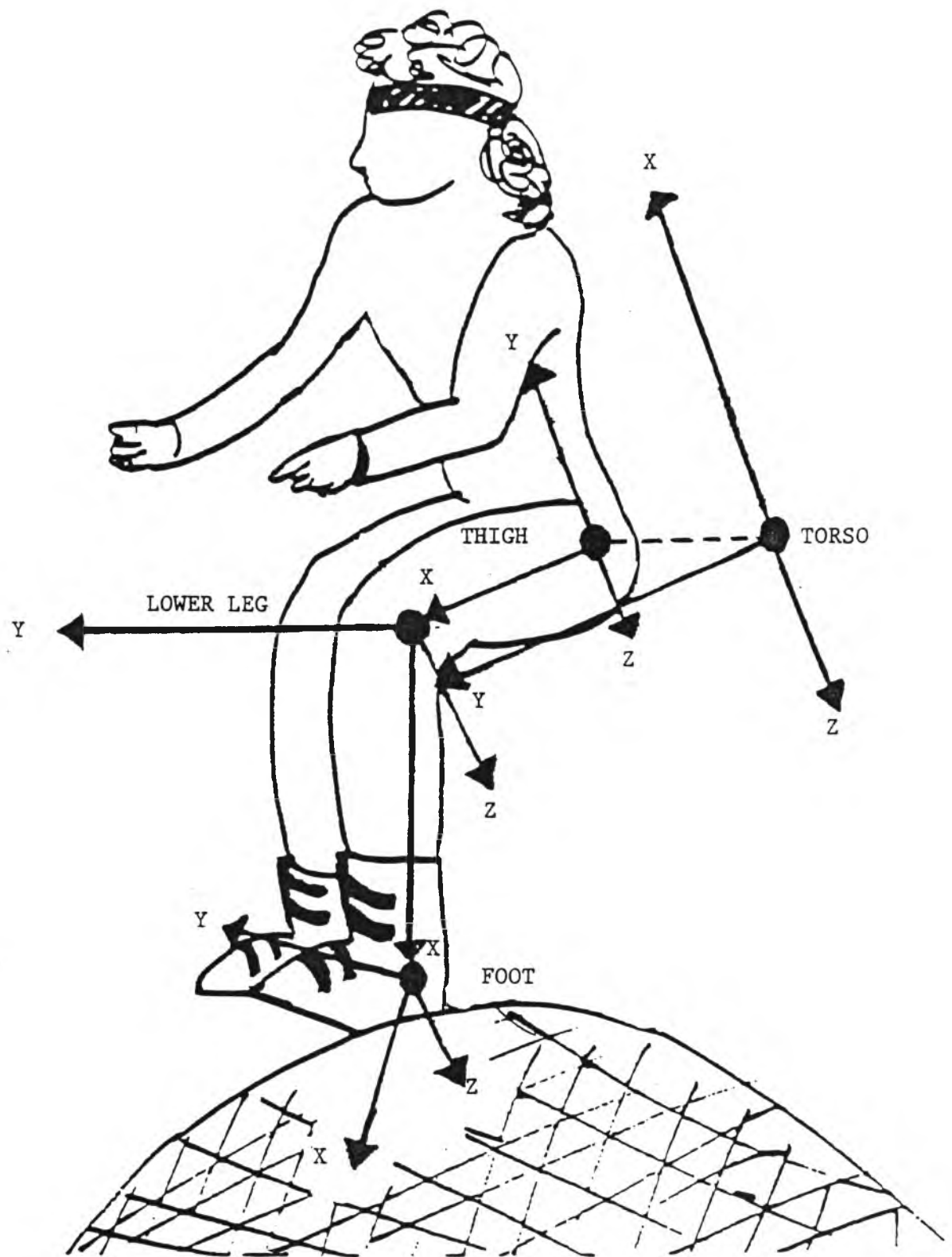


Figure 1.1: Anatomical frames of reference.

2. Anatomical frames of reference of the legs.

Orthogonal axes embedded in the legs such that positive x is the axis representing the long axis of the segment.

Positive x:

Origin: midpoint of line connecting the condyles of the tibia.

Direction: vertical, downward to origin of AFOR of foot.

Positive y:

Anterior perpendicular to positive x.

Positive z:

Right-hand mutually orthogonal to positive x and positive y.

3. Anatomical frames of reference of the thighs.

Orthogonal axes embedded in the thighs such that positive x is the axis representing the long axis of the segment.

Positive x:

Origin: midpoint of medio-lateral line connecting the centre of the greater trochanter of the femur with the pubic line.

Direction: vertical, downward to the origin of the AFOR of the corresponding leg.

Positive y:

Anterior perpendicular to positive x.

Positive z:

Right-hand mutually orthogonal to positive x and positive y.

4. Anatomical frame of reference of the torso.

Orthogonal axes embedded in the torso such that positive x is the axis representing the long axis of the segment.

Positive x:

Origin: midpoint of horizontal line connecting the most lateral aspects of the left and right greater trochanters.

Direction: vertical, up to midpoint of line connecting the lateral aspects of the left and right acromion processes

Positive y:

Anterior perpendicular to positive x.

Positive z:

Right-hand mutually orthogonal to positive y and positive x.

5. Joint Coordinate System Angles.

The Joint Coordinate System (JCS) angles described in this study are defined in Figure 1.2. (For further details see Section 3.8).

Although Figures 1.2(a) - 1.2(c) define the angles as specifically applied to the knee joint, they are similarly defined for the ankle and hip joints with the following differences:

- 1) Ankle : the long axis of the foot segment is the y axis (z remains the hinge axis).
- 2) Hip : the x axis direction for the torso is vertically upwards. The origin of both the thigh and the torso long axes is therefore located at the hip joint. This was defined as such to standardise the definitions so that the origin was always located at the proximal joint centre.

6. Absolute angles.

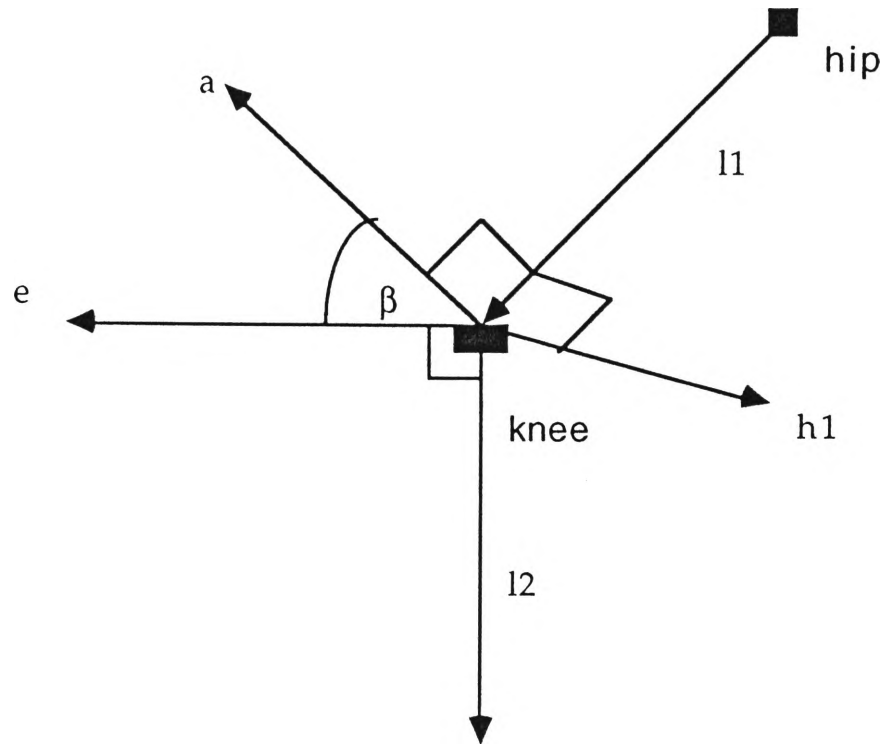
The absolute angle between two segments is defined as the angle occurring in the plane that the two segments lie.

7. Reference mogul.

The specific mogul upon which each subject was required to execute a turn for filming.

8. Trial.

Each time a skier executed a turn on the side of the reference mogul required for filming constituted a single trial.



a) Flexion/extension

Where:

β = the angle of interest,

$l1$ = the long axis of segment 1 (in this case x axis of the thigh),

$l2$ = the long axis of segment 2 (in this case x axis of the leg),

$h1$ = the hinge axis of segment 1 (in this case z axis of the thigh),

a = the cross product of $l1$ and $h1$, and

e = the cross product of $l2$ and $h1$.

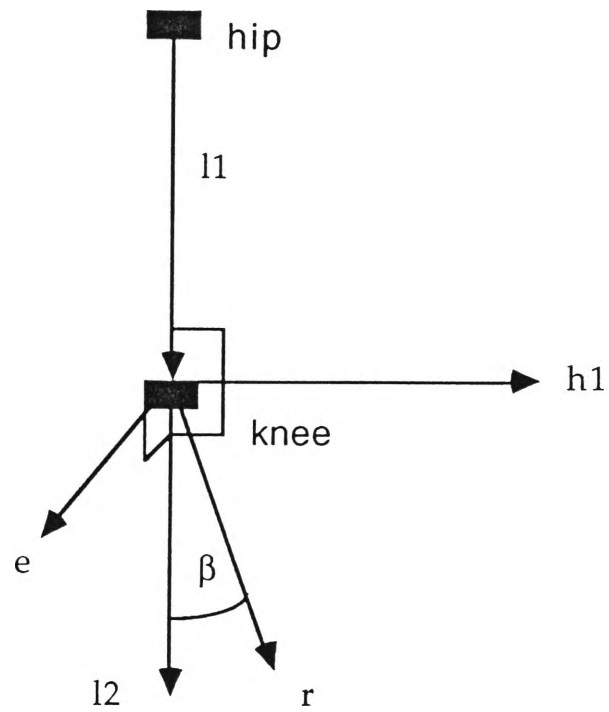
Figure 1.2: Joint Coordinate System angles used in this study as defined at the knee joint.



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c) Abduction/adduction (viewed from an anterior aspect).

Where:

r = the cross product of $h1$ and e .

1.6 A Glossary of Alpine Skiing Terms

Aerials:	freestyle manoeuvres performed in the air after a take-off ramp. An integral part of mogul skiing competitions but also a freestyle event in itself when multiple inverted manoeuvres are performed.
Bank-angle:	the angle of lean of the body necessary to maintain the line of application of the resultant of the centrifugal and gravity forces within the base of support during a turn.
Bindings:	mechanism of connecting ski boot to the ski. Composed of a heel and a toe section that permit release of the boot if forces applied in various directions are deemed sufficient to be potentially dangerous.
Carving:	specific turning technique where the edges of the skis are angled so that minimal lateral displacement occurs; that is, no side-slipping.
Downhill:	an alpine skiing event in which a minimal number of gates are used. This makes it the fastest of the traditional alpine events.
Edging:	preventing lateral movement of the skis by increasing the force applied in this direction to the metal edges of the skis.
Fall-line:	an imaginary line perpendicular to another such line of zero gradient to the slope. The fall-line is therefore the steepest, most direct line down the slope.
FIS:	The international governing body of alpine skiing (Federation International de Ski).
Freestyle:	skiing events in which style is the major judging criteria. It is composed of three events : moguls, ski ballet and aerials.
Gates:	sticks planted in the slope to define ski racing courses and must be negotiated by passing on specified sides. Many gates are used in the tight turning slalom events, less in the faster giant slalom or downhill events.

- Grooming:** preparation, usually overnight, of the ski slope by large mechanical graders, leaving a soft, even surface for skiers.
- Moguls:** bumps formed on a ski slope in the absence of mechanical grooming. Such ski slopes are the sites for freestyle mogul skiing competitions.
- Parallel turn:** advanced skiing turn in which the skis remain approximately parallel to each other.
- Schussing:** skiing directly down the fall-line with no turns. (From German; Schuß = shot).
- Side-slipping:** allowing the skis to slip laterally over the snow surface by decreasing the edge contact with the snow surface.
- Ski Ballet:** freestyle event in which the competitor performs slow, graceful dance manoeuvres on the skis and poles on a gentle gradient slope. In competition this is accompanied by music.
- Slalom:** alpine racing event with tightly spaced gates requiring many turns to negotiate.
- Speed skiing:** a straight run down a steep slope, highly dependent on aerodynamics. Actual velocity is the judged criteria. Speeds of over 200 km/h are regularly achieved.
- Tail:** posterior, flatter end of ski.
- Tip:** anterior, raised and pointed end of ski.

CHAPTER 2

A REVIEW OF RELATED LITERATURE

There was limited literature available on the kinematic analysis of alpine skiing (Morawski, 1973; Twardokens, 1985; Glenne and Von Allmen, 1979; Ikegami, Sakurai, Okamoto, Ikegami, Andon and Sodeyama, 1987) and even less available on mogul skiing. The only literature found pertaining to the biomechanical analysis of mogul skiing was found in freestyle instruction manuals (Australian Professional Ski Instructors, 1976; Canadian Freestyle Coaching Certification Level 2, 1984). Therefore this study could be seen as fundamental research leading to future study on technique, force quantification and injury prevention in skiing moguls. To provide an understanding of the three-dimensional kinematics of mogul skiing, literature from a relatively diverse research base was reviewed.

A thorough understanding of the three-dimensional, direct linear transformation (DLT) filming technique was necessary to obtain accurate results from the data collection procedure. The original literature upon which this technique was based (Abdel-Aziz and Karara, 1971; Van Gheluwe, 1974; Marzan and Karara, 1975; Shapiro, 1978) and subsequent research (for example Martin and Pongratz, 1974a, 1974b; Wood and Marshall, 1986; Hatze, 1988; Woltring and Huiskes, 1990) providing feedback and modifications to this technique was reviewed here. An overview of the description of three dimensional kinematics was also given.

Relevant literature was therefore drawn from the following areas :

- 1) Kinematic studies of general alpine skiing.
- 2) Kinetic studies of general alpine skiing.
- 3) Injury epidemiology and mechanisms in alpine skiing.
- 4) Three-dimensional kinematics.
- 5) The DLT filming technique.

2.1 Kinematic Studies of General Alpine Skiing

One research area of relevance to this study was that of kinematic studies of general alpine skiing. An understanding of these kinematics was necessary to allow adaptation to the more complex skill of mogul skiing.

2.1.1 Skier Mass Composition

The mass of the upper body of a skier is considered to be composed of the head, chest, upper extremities and the ski poles (Quigley and Chaffin, 1971; Twardokens, 1985; Read and Herzog, 1992). The effect of the ski poles is not considered important by some authors (Morawski, 1973). The approximate ratio of upper body mass to lower body mass (lower limbs, skis, boots and bindings) of the skier and equipment is 63 : 48 (Twardokens, 1985). Also the proportion of total body weight of the foot/ankle complex increases from 4% to 20% with the addition of ski equipment (Figure 2.1).

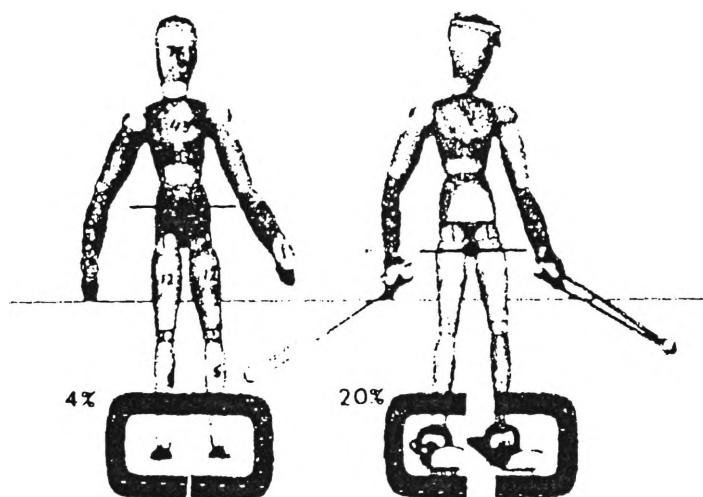


Figure 2.1: Changes in body proportions with the addition of ski equipment (from Twardokens, 1985, p.284).

In an analysis of the movements executed by a skier on a uniform slope, Twardokens (1985) found that the extra weight (approximately 10 kg) of the skis, boots and bindings, rigidly attached to the feet of the skier, lowers the skier's centre of gravity to 45% of the skier's height. The centre of gravity was therefore located at groin level between the thighs (Figure 2.1). This was considerably lower than the position of the total body centre of gravity without ski equipment.

2.1.2 Standard Stance

The process of skiing down a slope is achieved in its most simple form in a straight line with no turns. This style is called 'schussing' (German; Schuß = shot) and the body position can be either crouched or erect (Professional Ski Instructors of America, 1966, 1970; Philipp, Zeilinger and Meßmann, 1967; Quigley and Chaffin, 1971; Mariacher, 1989). The erect position (Figure 2.2) illustrates the standard skiing stance.

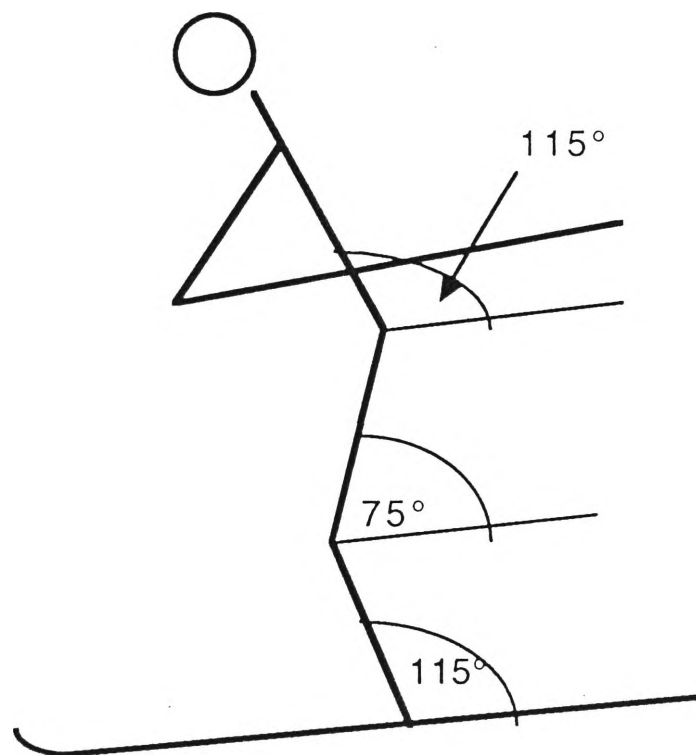


Figure 2.2: The standard skiing stance (after Mariacher, 1989).

In Figure 2.2 the ski is taken as the right hand horizontal and all angles are measured relative to this right hand horizontal. The tibia resting against the internal, anterior surface of the ski boot produces an angle at the leg approximating the dorsiflexion angle of the modern ski boot (Quinn, Mote and Skinner, 1989). The knee is slightly flexed and the torso is aligned parallel to the legs (Mariacher, 1989). The angles at the ankle, knee and hip are therefore approximately 115° , 75° and 115° respectively. The crouched position is achieved by greater flexion at the knee and hip joints and is a position adopted almost exclusively for schussing in order to minimise aerodynamic drag forces.

2.1.3 Turning

When the mechanical purpose of skiing is not attainment of maximum velocity, a skier will, if competent, perform turns. This study will only analyse the parallel turning technique of advanced skiers as only advanced skiers are capable of fluently skiing a mogul run.

The advanced, parallel turn is initiated by a kinetic chain to provide force sufficient to complete a turn. This kinetic chain originates in the muscles of the hips and continues through the knee joints to the ankles where the force is applied to the skis' edges. "The feet alone would have enough power to initiate a turn but not enough range to complete it. The turning force in advanced skiing is thus provided by the rotation of the lower limbs against the relatively stable, larger mass of the upper body" (Twardokens, 1985). A lateral friction force (see Section 2.2.1 below) is developed by 'edging' the skis into the snow in order to overcome centrifugal and gravity forces (Glenne and Von Allmen, 1979).

The upper body follows the skier's general path of travel while the lower body and the skis will generally describe a larger radius arc as the result of the turning action of the skis (Canadian Freestyle Coaching Certification Level 2, 1984). The upper body will therefore follow a more direct downhill trajectory with the legs forming arcs on either side of this line. A skier can emphasize either speed through a turn or sharpness of the turn by the amount of edging. The greatest speed is achieved by 'carving' a turn. A turn is carved by severely edging the skis during a turn to produce the greatest possible angle between the snow surface and the base of the ski, thus allowing the metal edges of the ski to obtain the maximum hold on the snow surface (Glenne and Von Allmen, 1979). This edging is in turn achieved with large knee and hip abduction. The actual twisting and edging mechanism combined is composed of medial rotation, flexion and adduction of the outside

(or downhill), major weight bearing limb of the turn and lateral rotation, flexion and abduction of the inside (uphill) leg (Louie, Kuo, Gutierrez and Mote, 1984; Twardokens, 1985; Mariacher, 1989).

The skier's centre of gravity therefore always travels a shorter distance than the skis during a turn (Morawski, 1973; Canadian Freestyle Coaching Certification Level 2, 1984; Twardokens, 1985) indicating a lean angle (or 'angulation' of the hip and/or knee) and this produces the body 'bank angle'. The intensity and speed of a turn are dictated by this bank angle and the resulting edging (Morawski, 1973; Glenne and Von Allmen, 1979).

2.1.4 Application to Skiing Moguls

Almost all research concerned with an analysis of skiing was based upon the assumption that the slope was smooth and the snow surface of uniform condition (Quigley and Chaffin, 1971; Morawski, 1973; Sack and Albrecht, 1973; Watanabe and Ohtsuki, 1977; Glenne and Von Allmen, 1979; Twardokens, 1985; Luethi and Denoth, 1987). However, as Ikegami *et al.* (1987) stated this was rarely the case in field conditions and only few authors have incorporated varying snow conditions (Wittmann, 1974; Neukomm and Nigg, 1974) or uneven terrain (Ikegami *et al.*, 1987; Read and Herzog, 1992) in their research on alpine skiing.

When mogul skiing, disturbances of equilibrium are continuous and occur more frequently than when skiing on a smooth slope. In order to ski moguls well, a skier must be competent at a wide repertoire of skiing skills to negotiate the continually, rapidly changing terrain (Australian Professional Ski Instructors, 1976; Canadian Freestyle Coaching Certification Level 2, 1984).

The fastest, 'most exciting' (Canadian Freestyle Coaching Certification Level 2, 1984) form of mogul skiing is turning in the 'fall-line'. Skiing moguls in the fall-line is the basis of freestyle mogul skiing and the Canadian Freestyle Coaching Certification Level 2 (1984) recommended that competitive mogul skiers wishing to score highly should in all cases ski directly down the fall-line. In skiing this line the skier's speed will be relatively high and greater effort will be required to turn the skis. This is a result of the skis flexing when both the tail and tip are in contact with consecutive moguls with the force applied to the mid-section of the ski causing the ski flexion between the moguls. Greater muscular effort and

coordination is required to prepare for the following turn in the relatively short time period available before contact is made with the next mogul.

There are various techniques of skiing moguls in the fall-line. In well formed, relatively uniform moguls the sides of moguls can be used in the 'rebound' or 'wriggling' (Hurn 1990; Blundell, 1992) technique, where the skier uses the sides of evenly spaced moguls to rebound into the next turn. As the moguls get either closer together or less well defined, the 'rooftop' technique, where the skier skis over the crest of the moguls while setting the edges to control speed becomes the preferred technique (Canadian Freestyle Coaching Certification Level 2, 1984). Both these techniques are evident on the competitive mogul skiing circuit. The rebound technique often scores higher due to the impression of greater turning speed through the moguls. In this technique the skier keeps the skis very close together and the upper body is positioned directly above the feet. The turns are executed almost solely with the middle third of the skis' edges rebounding off the sides of the moguls. The 'rooftop' technique is more dependent on a standard, technical carving turn with greater knee and hip angulation together with almost the complete length of the skis' edges being utilised in the execution of the turn providing a more complete turn on each mogul (Blundell, 1992; St. Pierre, 1992)

The description of mogul skiing given above is based entirely on instruction manuals and personal suggestions made by experienced skiers. No literature on scientific studies conducted on mogul skiing have been found. The work done by Ikegami *et al.* (1987) on skiing over bumps in a straight line and Read and Herzog (1992) on landing after a skiing jump complement the previously mentioned literature and provide an indication of the kinematics of skiing mogul run.

Ikegami *et al.* (1987) gave a two-dimensional kinematic description of the movements necessary for a skier to maintain balance despite the rapid changes of ground reaction force from the snow surface experienced when skiing in a straight line over two uniform bumps constructed on a gentle slope. In this study a comparison was made between skilled and intermediate skiers and it was found that accelerations in the lower body and the range of joint motion at the knees and hip of the skilled skiers were large, whereas the accelerations and trajectory of the upper body were relatively stable (Figure 2.3).

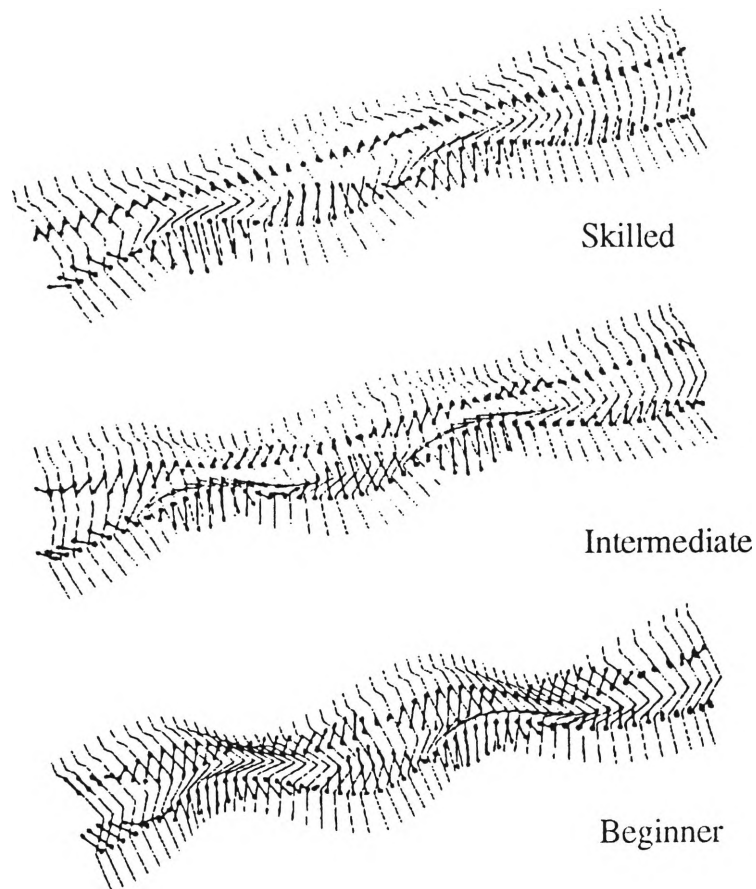
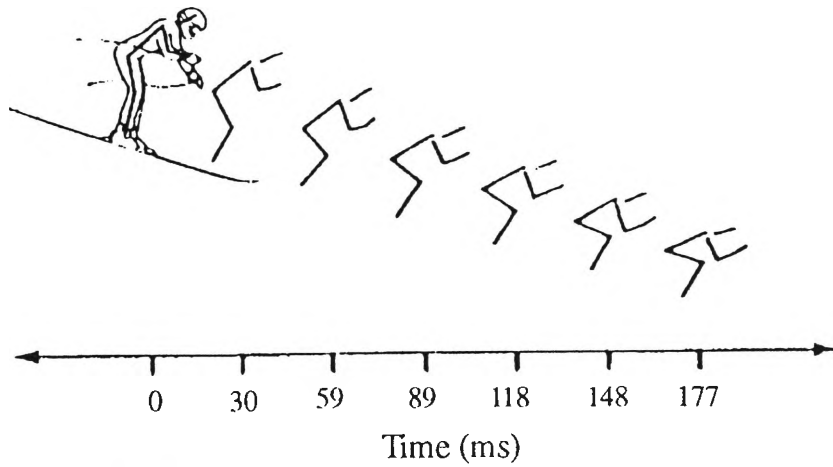


Figure 2.3: Body positions when skiing over a bump (from Ikegami *et al.*, 1987, p.297).

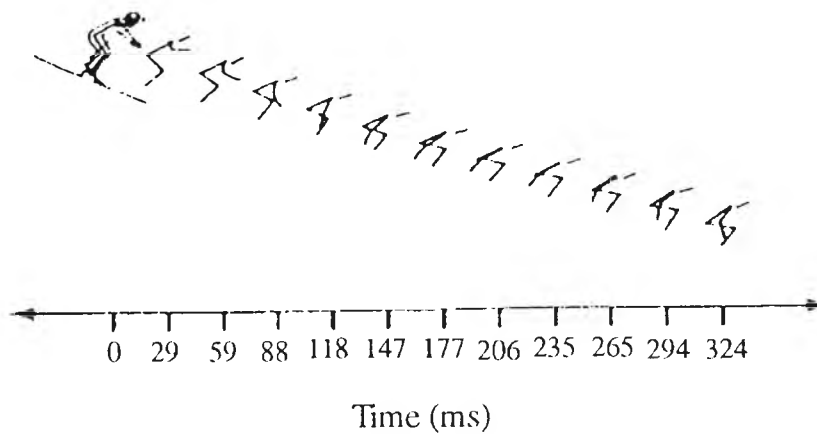
The skilled skiers actively extended at the hip and knee immediately after skiing over the bump. This prevented the skier's body from falling down the far side of the mogul and from receiving the impact force of the snow surface after the bump. This was the technique suggested by skiing technique manuals (Australian Professional Ski Instructors, 1976; Canadian Freestyle Coaching Certification Level 2, 1984; Shedden, 1986).

The Australian Professional Ski Instructors (1976) recommended an additional movement be incorporated in mogul skiing that was not required in general, smooth slope skiing. This movement was to reduce the effect of the impact from the mogul. The skier was advised to retract the legs by contracting the abdominal muscles and to follow this with a subsequent extension of the legs as the crest of the mogul was passed: "By yielding to the mogul in the legs, the upper body can travel without a jolt, [while] balance and snow contact is maintained" (Australian Professional Ski Instructors, 1976, p. 16).

Read and Herzog (1992) compared the landings of two competitors in a World Cup downhill race (Figures 2.4 and 2.5).



(a)



(b)

Figure 2.4: Landing form after a jump (from Read and Herzog, 1992, p.64).

One competitor was considered to be landing in 'poor form' (Figure 2.4b) due to a possibly greater likelihood of knee injury (anterior cruciate ligament (ACL) damage) when landing in this manner. This potentially more dangerous style was characterised by the upper body centre of mass (CM) being positioned further posterior relative to the knee joint centre when subjected to the force of landing. The style described as 'good form' (Figure 2.4a) consisted of a more flexed body position, thus maintaining the CM more anteriorly.

By comparing the landing forces after a jump to the forces experienced when a skier strikes a mogul, the positions described by Read and Herzog (1992) indicated a possible injury mechanism also encountered in mogul skiing. The different positions described by Read and Herzog (1992) are graphically presented in Figure 2.5 in which Subject 1 is landing in 'good form' and Subject 2 in 'poor form'.

If the force of striking the mogul resulted in the skier leaning back, a strong contraction of the quadriceps muscles would be necessary to maintain the upper body position over the legs. This quadriceps contraction combined with an anteriorly directed force on the tibia from leaning back on the ski boot was suggested by Read and Herzog (1992) as a potential injury mechanism of the ACL. The backward lean also positioned the skier's centre of gravity further posteriorly resulting in the line of gravity falling well towards the tail of the skis, making the skier less balanced and subject to a loss of control. In order to prevent this injury mechanism from occurring the skier should adopt a position equivalent to the straight trajectory of the upper body as described by Ikegami *et al.* (1987). A skier should flex at the ankles and hips to maintain a forward leaning position and therefore achieve greater balance with less muscular effort.

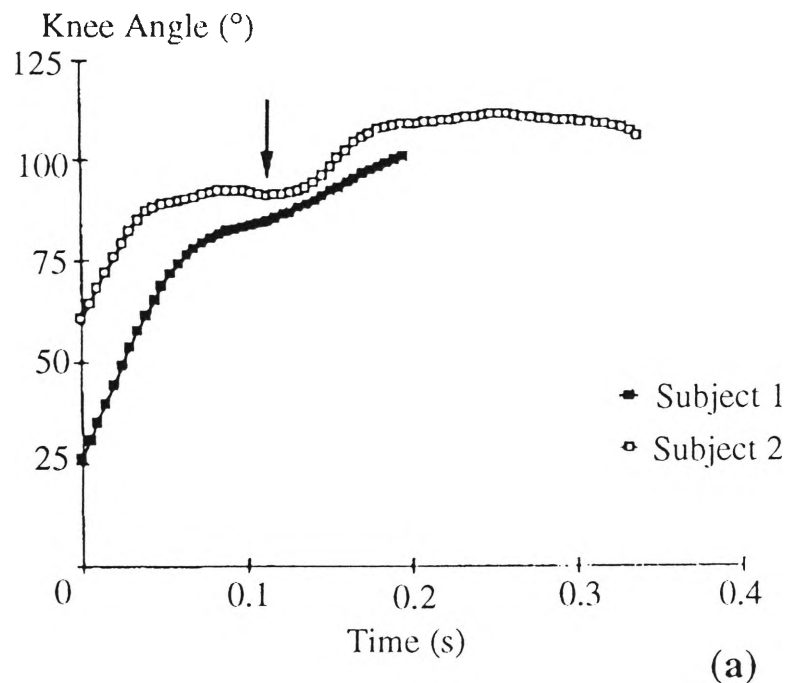
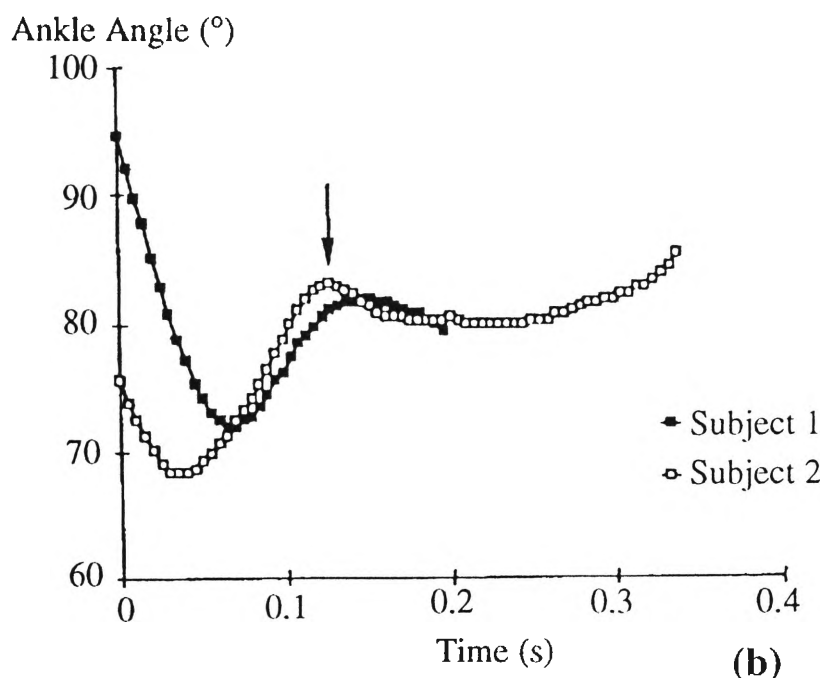


Figure 2.5: Leg joint angles when landing from a jump (from Read and Herzog, 1992, pp. 74,75).



In Figure 2.5a, the arrow indicates the phase of movement for Subject 2 where the knee angle becomes slightly more extended.

Turning in moguls is aided by the slopes of the bumps. The horizontally directed component of the ground reaction force of the slope of the bump, being perpendicular to the fall line of the slope, assists the lateral edging force (Glennie and Von Allmen, 1979) to produce the turn (see Section 2.2.1). In a similar fashion this slope will, in itself, produce a body bank angle (Morawski, 1973) to produce hip and/or knee angulation. Both the previously mentioned rebound (or 'wriggling') and carving (or 'rooftop') techniques are therefore complemented in different ways by the presence of moguls. The rebound technique is possible due to the consecutive moguls effectively braking the rebound off the previous mogul and providing a reaction force to rebound into the next mogul (Hurn, 1990). The carving technique is enhanced by the greater effective control and angulation possible due to the moguls' angle. Greater knee and hip flexion is necessary to absorb the bump and reduce the force experienced by the upper body (Hurn, 1990) than in the execution of a turn on an even, uniform gradient slope.

The irregularity of the terrain combined with the complexity of the motions involved in mogul skiing are factors this study must incorporate in its methodology. The major

prerequisite is that all motions executed in a mogul skiing turn can be analysed, this includes flexion/extension at the ankle, knee and hip joints, any hip or knee angulation (measured as abduction/adduction at the hip, varus/valgus at the knee) and internal/external rotation of the tibia. The analysis of these motions, when observed in context with the above mentioned literature on the kinematics of alpine skiing and studies done on the moments and forces most likely to cause injury in skiing (Sections 2.2.3, and 2.3) was intended to provide a description of potential injury mechanisms in mogul skiing.

2.2 Kinetic Studies in General Alpine Skiing

When describing the motions of the human body it must be understood that these motions were dependent on the forces producing them whilst simultaneously being responsible for the production of further forces. Feltner and Dapena (1989) stated that "A full understanding of the cause-effect mechanisms that produce any body motion requires the use of a model to link the kinematics of the motion with the kinetic factors responsible for it,"(p. 403).

Despite the importance of such kinetic data in understanding the techniques and possible injury mechanisms of mogul skiing, the quantification of forces involved in skiing moguls is beyond the scope of this study. The kinematic analysis provided in this study is however necessary for the later identification of these forces. Previous studies on the kinetics of alpine skiing have provided valuable information for kinematic study and a brief review of literature concerned with the kinetic description of skiing is therefore given here.

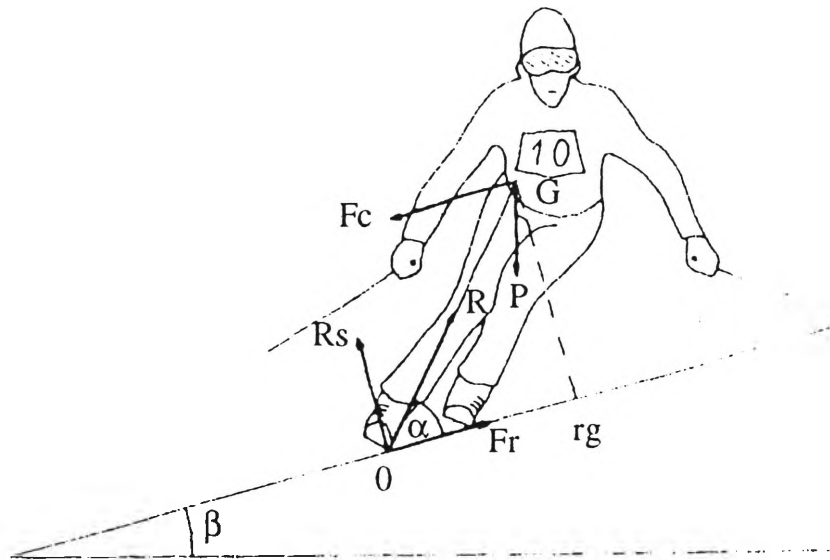
2.2.1 Skiing Forces

Figueras, Llobet, Buló, Morgenstern and Merino (1985) explored the possibility that the restriction of lateral displacement of the skis during turning may be the cause of knee injuries occurring while the skier does not actually fall. Figueras *et al.* (1985) developed a simplified theoretical model (Figure 2.6) to describe the forces acting upon a skier.

The ski, binding, boot and ankle were thought of as a rigid body. The skier's linear speed and the environmental conditions were considered constant. Two forces, the weight (P) and the centrifugal force (F_c) acted on the skier's centre of gravity. The perpendicular

force (R_s) against the surface of the snow would cause the edge of the ski to penetrate the snow until the projection of the surface of contact equalled the resistance of the snow. Figueras *et al.* (1985) calculated that if the edge-setting angle (α) was kept within the limits of the snow resistance, that is between 30° and 60° , then no skidding would take place during the turn. This constituted the restriction to lateral displacement of the skis resulting in a possible injury mechanism in that the centrifugal force (F_c) was directly opposing this resistance and the musculo-skeletal system of the downhill leg, especially the ligaments of the knee were acting as a lever to balance these two forces.

When no turns are being executed and the skier is schussing down the slope in a straight line, the skier is acted upon by gravity, inertia, snow friction and air friction (Glenne and Von Allmen, 1979). An outline of forms of friction in skiing is also given in Outwater (1970). As mentioned in Section 2.1.3, the speed or sharpness of a turn can be optimised by either carving or skidding.



Where :

G = centre of gravity,

F_c = centrifugal force,

P = weight of skier,

F_r = radial force,

rg = turning radius of centre of gravity,

R_s = force perpendicular to the slope,

0 = radius of the trace,

β = angle of side-slipping,

α = angle of equilibrium, and

R = resultant forces acting on the centre of the ski.

Figure 2.6: Forces on a skier (from Figueras *et al.*, 1985, p.142).

Sharp turning is determined by a high lateral friction force (edging) which is defined as :

lateral friction force = lateral gravity force - lateral air friction force

$$F = W \sin \theta (\alpha + \beta) - \frac{C_D A \rho V^2}{2} \sin \beta \quad (1)$$

Where:

F = force lateral to skier direction, exerted by skier

W = weight of skier

θ = angle of fall-line slope

α = angle between skier direction and fall-line

β = angle between ski and skier direction

C_D = drag coefficient of skier

A = frontal area of skier

ρ = air density

V = skier velocity

From Glenne and Von Allmen (1979)

When side-slipping, a skier usually remains in the standard stance, facing perpendicular to the fall-line whilst slipping laterally at an angle $(\alpha + \beta)$, in Equation 1) to the direction of the skis (Mariacher, 1989). At large angles of side-slipping, $(\alpha + \beta)$ approaches 90° . Small angles of side-slipping or no side-slipping are referred to as carving (Glenne and Von Allmen, 1979). By applying Equation 1 to mogul skiing the lateral frictional force (F) will be combined with a lateral supportive force normal to the ski base provided by the angle of the mogul. This is similar to the supportive force provided by soft snow (Glenne and Von Allmen, 1979).

The frictional force (F) is largest after the skier has crossed the fall-line as gravity and the deceleration force pulling to the outside of the turn must be overcome. As a result, the radius of the turn will increase after the fall-line has been crossed (Walner, 1964). The impulse created by this increased combination of forces in the latter sections of a turn is absorbed over a certain amount of time in general alpine skiing. However in mogul skiing

this absorption time is often greatly reduced as the skier decelerates rapidly when striking the mogul following a turn. The frictional force F is therefore larger and must be absorbed by the soft tissues of the skier's body.

The equation for the calculation of the air friction force is:

$$F = \frac{C_D A \rho V^2}{2} \quad (2)$$

Where:

F = force opposing the skier due to air resistance

C_D = drag coefficient of skier

A = frontal area of skier, i.e. total area directly
opposing the air flow

ρ = air density

V = skier velocity

From De Koning, De Groot and Van Ingen Schenau (1989)

A number of authors have studied skiers in various positions in wind-tunnel experiments to study the effects of aerodynamic forces on the skier (Watanabe and Ohtsuki, 1977; Luethi and Denoth, 1987).

Whilst measuring the effects of different forces on theoretical time differences of skiers in a wind-tunnel, Luethi and Denoth (1987) found drag force to be the most influential force, accounting for 49% of any time difference. Mass (29%), frontal area (21%), and lift (1%) all provided considerably less influence. Watanabe and Ohtsuki (1977) calculated drag forces of up to 256.27 N at wind velocities of 30 m/s with the skier in an upright posture. In a tucked position (same as the crouched position described by Quigley and Chaffin, 1971) the drag force was reduced to 115.64 N at the same wind velocity. Elementary changes in stance therefore accounted for a difference of approximately 141 N force opposing the skier.

2.2.2 Forces on the Lower Limb

The high rate of injury to the lower limb in skiing (see Section 2.3) has prompted extensive research on forces experienced by the lower limb during alpine skiing (Asang, 1974; Kuo, Louie and Mote, 1983; Louie *et al.* 1984; MacGregor and Hull, 1985; Mote, 1987; Mote and Kuo, 1989; Maxwell and Hull, 1989; Quinn *et al.* 1989, Read and Herzog, 1992).

A combined torsional moment and valgus or flexion force is the most commonly described form of loading responsible for the high incidence of medial collateral ligament (MCL) injury in skiing (Outwater, Mastro and Ettlinger, 1969; Asang, 1974; Johnson, Pope, Weisman, White and Ettlinger, 1979). That is the tibia twists inside the ski boot when torsional moments are applied to the limb through the ski. At the same time the cruciate ligaments are stretched during forward and backward bending of the limb. Torsion of the limb combined with external rotation of the limb will stretch the collateral ligaments, especially the MCL (Mote, 1984). In a study examining tibial stresses resulting from various external loadings applied to a ski Piziali (1973) related torques produced at the ligaments to rotations of the long bones of the leg within the joint capsules. The torques were positive or negative depending upon the direction of rotation of the long bone. Although Piziali (1973) based his findings upon cadaver specimens the results obtained are of value to this study in that a relationship between torques required at the leg joints to produce the resulting rotations at the ligaments is provided. The results support Twardokens' (1985) statement relating the force required to complete a turn with the range of motion necessary at the foot and hip to do so. Although the torque provided at the ankle joint in Figure 2.7 was sufficient for the execution of a standard parallel turn it was the greater range of motion at the hip which permitted execution of the turn despite greater torque being necessary to produce this.

Piziali's study was concerned with measuring the forces necessary at the joints for the motions required in skiing in an attempt to quantify frequency ranges of forces for binding release. However as Mote (1987) stated: " The actual forces during skiing and those capable of causing injury cannot be distinguished from each other. " (p. 323) Quinn *et al.* (1989) found the forces and moments at the knee producing internal and external rotation were three-dimensional and Mote (1987) stated that torsional moments, and especially bending moments occurring during general skiing were sufficient to cause injury to the knee and tibia if no other mechanisms (flesh/muscle mass) were to support the limb.

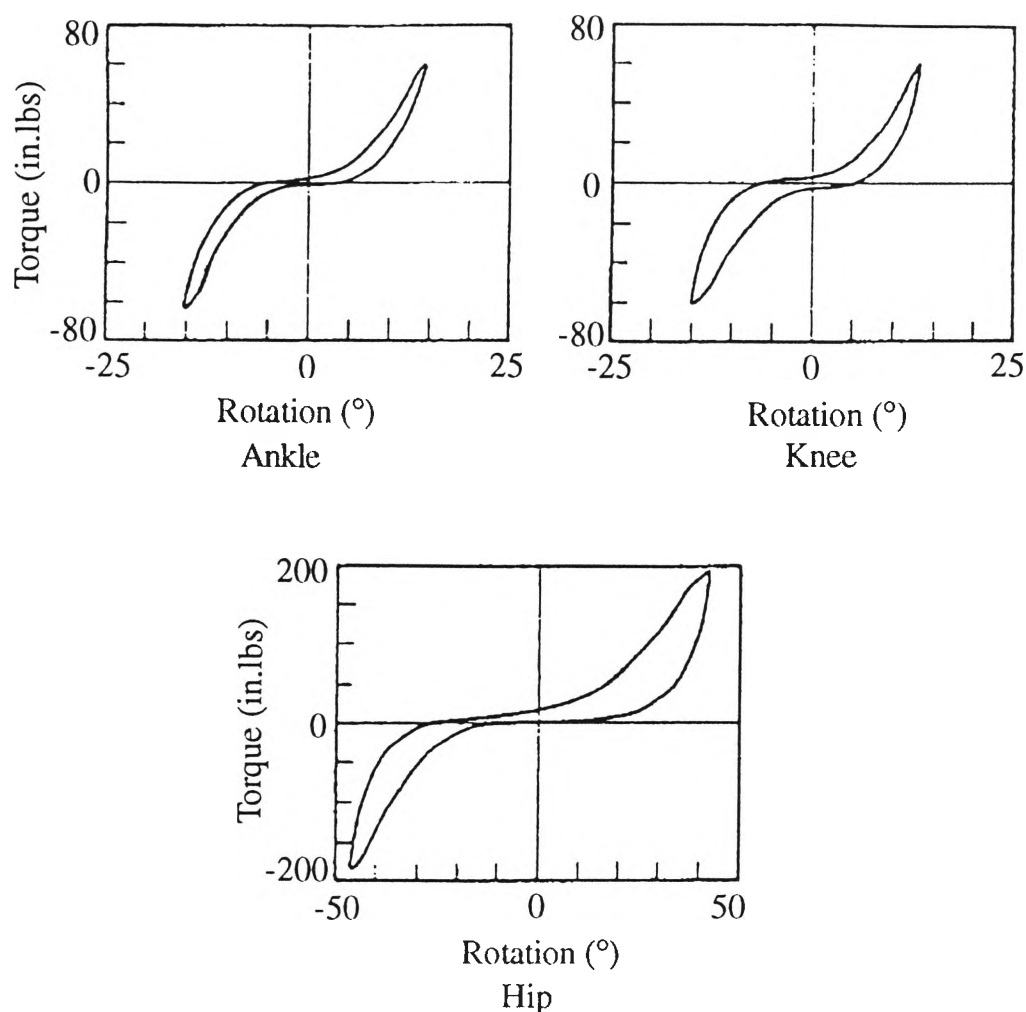


Figure 2.7: Torque-rotation plots for the ankle, knee and hip of a preserved specimen (from Piziali, 1973, p. 309).

The major safety measure in skiing designed to prevent injuries to the leg is the ski release binding. This is a mechanism designed to attach the ski boot to the ski, having been described as attaching the long lever-arm of the ski (Burns, Steadman and Rodkey, 1991) to the biological components of the leg. The basic function of this is to interrupt the force transmission between the ski and the leg before it reaches potentially dangerous levels. The second major function of ski release bindings is the transmission of all forces that are not dangerous to the legs through the segments of the lower extremity to the skis for steering and ski control (Wittmann, 1974). The binding must therefore fulfil two somewhat contradictory roles; releasing when loads on the legs are excessive but not releasing prematurely as a result of any high loads experienced during controlled skiing. A premature release of the bindings, especially if it occurs whilst the skier is travelling at any

great speed, can result in injuries due to a loss of control experienced when the skier is no longer securely connected to the ski. In this situation injury can be caused by collisions with the loose ski, with another skier or with any obstacle on the skifield. These sometimes fatal accidents can therefore not be neglected when attempting to prevent the leg damage encountered if a binding will not release.

The importance of bindings in ski injury prevention has attracted the attention of a number of authors in analysing the basic function and modification of the ski release binding (Piziali, 1973; Wittmann, 1974; Perryman, 1975; Roberts, 1980; Lieu and Mote, 1980; Kuo *et al.*, 1983; Louie *et al.*, 1984; MacGregor, Hull and Dorius, 1985; Engel, Hofreiter and Vogel, 1985; Maxwell and Hull, 1989). Ski bindings may not be able to release in some cases even when the forces may exceed the threshold of injury to the leg. An example of this is landing on the upward side of a mogul (Roberts, 1980) where the direction of the force and resultant loading on the ski may not allow the mechanism to function. The nature of a mogul field can produce three-dimensional forces and moments across the joints of the leg, some of which may exceed the force necessary to cause injury but will not result in a binding release. Mogul skiing is therefore an extreme test of binding function with a multitude of forces operating at different angles and positions on the skis over a short period. The fact that bindings may not release as a result of the variety of forces encountered in skiing moguls makes it necessary to identify the kinematics responsible for these forces and this necessity forms the basis of this study. This may then contribute to further research concerned specifically with binding function in mogul skiing.

Gruber, Denoth, Ruder, and Stüssi (1990) provided an inverse dynamics explanation of how accelerations experienced in impact type sports produce forces transmitted at the joints. The accelerations studied were negative accelerations or decelerations of the body parts as a result of the impacts. This can presumably be related to the impacts occurring during skiing in general and mogul skiing specifically. Neukomm and Nigg (1974) found that accelerations of the tibia increased quadratically with an increase in skier velocity whilst accelerations of the vertex and ilium increased linearly. These accelerations measured at the tibia were approximately seven times greater when compared to those experienced by subjects running on a flat surface. Accelerations at the hip were approximately equal to those in running. The greater external forces in skiing were therefore assumed to be absorbed by the muscles, joints and tendons of the leg. There appeared to be no greater upper body stress in skiing than in running.

2.3 Epidemiology of Skiing Injuries

The unaccustomed concentration of mass further down the body during alpine skiing (Twardokens, 1985; Raskulinecz and Bahniuk, 1979) combined with the high dependence of the motions of skiing on the lower limbs (Morawski, 1973; Asang, 1974; Wittmann, 1974; Diel and Mote, 1980; Louie and Mote, 1982; Ikegami *et al.*, 1987; Mote, 1987) placed additional stress on the lower limbs. Further, the long-lever arm of the ski attached to the foot (Burns *et al.*, 1991) and the stiff nature of modern ski boots (Hauser and Schaff, 1987; Quinn *et al.*, 1989) magnified any abnormal motion and transmitted the above-mentioned forces primarily to the tibia, femur and knee, but also to the hip. These stresses were transmitted by the ligaments of the knee causing angular and torsional injuries such as ruptures or tearing of the ligaments (Burns *et al.*, 1991).

Knee injuries account for between 20% and 30% of all skiing injuries (Outwater *et al.*, 1969; Johnson and Ettlinger, 1982; Piziali, 1982; Figueras *et al.*, 1985; MacGregor and Hull, 1985; Maxwell and Hull, 1989; Mote and Kuo, 1989) with the most common knee injury being damage to the MCL (Marshall, Warren and Fleiss, 1975; Johnson *et al.*, 1979; Piziali, 1982; Burns *et al.*, 1991). The probability of damage to the MCL is increased in mogul skiing due to the increased likelihood of an irregular ground reaction force producing an exaggerated torsional or flexional response at the knee. As has already been mentioned (Section 1.1), the high injury rate among many elite mogul skiers is testimony to this high probability of injury to the ligaments of the knee.

The ACL was also frequently injured in alpine skiing (MacGregor and Hull, 1985; Read and Herzog, 1992). Read and Herzog (1992) speculated that many injuries of the ACL were due to a certain posture in which the skier was leaning back trying to regain balance after an unexpectedly large impact on the base of the skis. The ski boot pushed forward on the tibia, loading the ACL and this was coupled with a violent contraction of the quadriceps muscle group. This was a situation possibly encountered in mogul skiing when the skier extended the legs after turning on the previous mogul and then the sudden impact force of the next mogul on the skis produced an involuntary, posterior motion of the upper body. This could produce a position similar to that described by Read and Herzog (1992). Once in this position the skier would have to regain balance before the next mogul was encountered.

2.4 Three-Dimensional Kinematics

The context of this study required a description of mogul skiers in three-dimensional space and a description of general motion in three dimensions is therefore necessary in order to apply the three-dimensional filming technique outlined in Section 2.5. The study of three-dimensional motion is largely dependent upon geometric representations of certain axes and rotations about these axes. By making the assumption that the limbs of the human body are rigid, these rotations can be compared to the movements of the human body.

2.4.1 Direction Cosines

To be able to define the position of a rigid body in three-dimensional space, the coordinates of three non-colinear points on the body need be known (Rodrigue, 1840 as cited in Lafortune, 1984; Berme, Cappozzo and Meglan, 1990; Woltring and Huiskes, 1990). The definition of a rigid segment from three non-colinear points is described in Figure 2.8.

In Figure 2.8, a vector R_1 defines the location of one point (P_1) relative to the origin of a global coordinate system. Two vectors (R_2 and R_3) connecting P_1 to the other two points (P_2 and P_3) define a plane. Their cross product, R_4 , is a vector normal to this plane. Taking the cross product of R_2 with R_4 defines R_5 , thus producing a triad of mutually orthogonal vectors; R_2 , R_4 , and R_5 . If each of these vectors is divided by its own length, a unit coordinate system is obtained (Berme *et al.*, 1990).

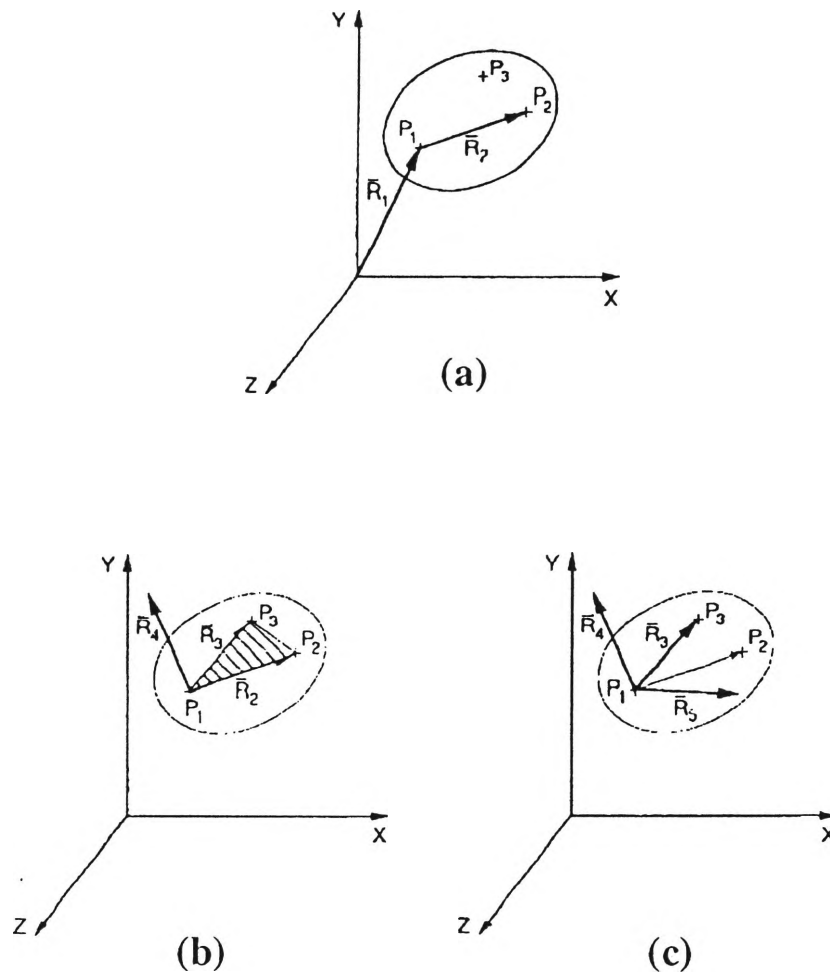


Figure 2.8: The definition of a rigid body in three-dimensional space by three non-collinear points on that body (from Berme *et al.* (1990) p. 90).

This unit coordinate system (x , y , and z) is fixed within the above rigid body and each unit vector is represented by its components in the global coordinate system (X , Y , and Z). Any rotating motion of the rigid body relative to the global system will render the x , y , and z components time variant. If one considers a unit vector and its components and divides these components by the length of the vector, the cosine of the angle that the vector makes with each of the corresponding X , Y , and Z axes is obtained (Figure 2.9).

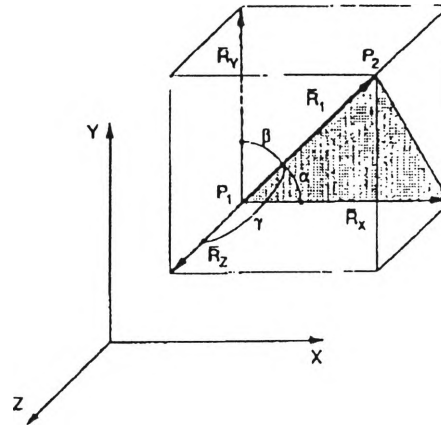


Figure 2.9: The direction cosines (from Berme *et al.*, 1990, p. 91).

These values are the direction cosines of the vector and are designated by l , m , and n . Therefore the direction cosines of a unit vector along x are lx , mx , and nx ; along y are ly , my , and ny ; and along z are lz , mz , and nz . The nine direction cosines define the orientation of one coordinate system to the other.

2.4.2 Euler Angles

The Euler angles are defined as three successive angles of rotation (Meriam, 1975; Miller, Shapiro and McLaughlin, 1980; Grood and Suntay, 1983; Berme *et al.*, 1990; Legnani, 1992; Grood, 1992; Woltring, 1992). There are a number of descriptions of the Euler angles but the most common is that described by Berme *et al.* (1990) and Legnani (1992). If the mobile coordinate system (x , y , and z) is initially coincident with the global coordinate system, the first rotation (ϕ) of the mobile frame is about the mutual z axis (z)

to give the position of x_1 , y_1 and z_1 . The second rotation (φ) is about the new x axis (x_1) to give x_2 , y_2 , and z_2 . Finally a rotation (θ) about the new z axis (z_2) places the mobile frame in its final position; x_m , y_m , and z_m .

A matrix known as a transformation matrix can relate the components of a vector in two different coordinate systems if the direction cosines relating the components of the vector are known (Berme *et al.*, 1990). Such a transformation matrix takes the form :

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \begin{bmatrix} \Delta X & \Delta Y & \Delta Z \\ \phi & \varphi & \theta \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} \quad (3)$$

Where:

X , Y , and Z = the three-dimensional coordinates of one point,

ΔX , ΔY , and ΔZ = the linear distance this point has moved; that is the components of the translation vector,

ϕ , φ , and θ = the three Euler angles, and

e_1 , e_2 , and e_3 = the distances, or transformation measurements (along the axes of the local coordinate system) of this point to the origin of the local coordinate system.

Grood and Suntay (1983) described a joint coordinate system (JCS) to allow the relative motion of two bodies to be specified. By defining the tibia and the femur as these two bodies, this system was applied specifically to the knee. The three rotation axes that described this joint coordinate system were:

- 1) x : a body fixed axis in the femur perpendicular to the femoral sagittal plane and rotations about this were flexion/extension,
- 2) y : a body fixed axis coincident with the long axis of the tibia, rotations about this were internal/external tibial rotation,
- 3) z : a floating axis, common perpendicular to both fixed axes, rotations about this were abduction/adduction, (see Figure 2.10).

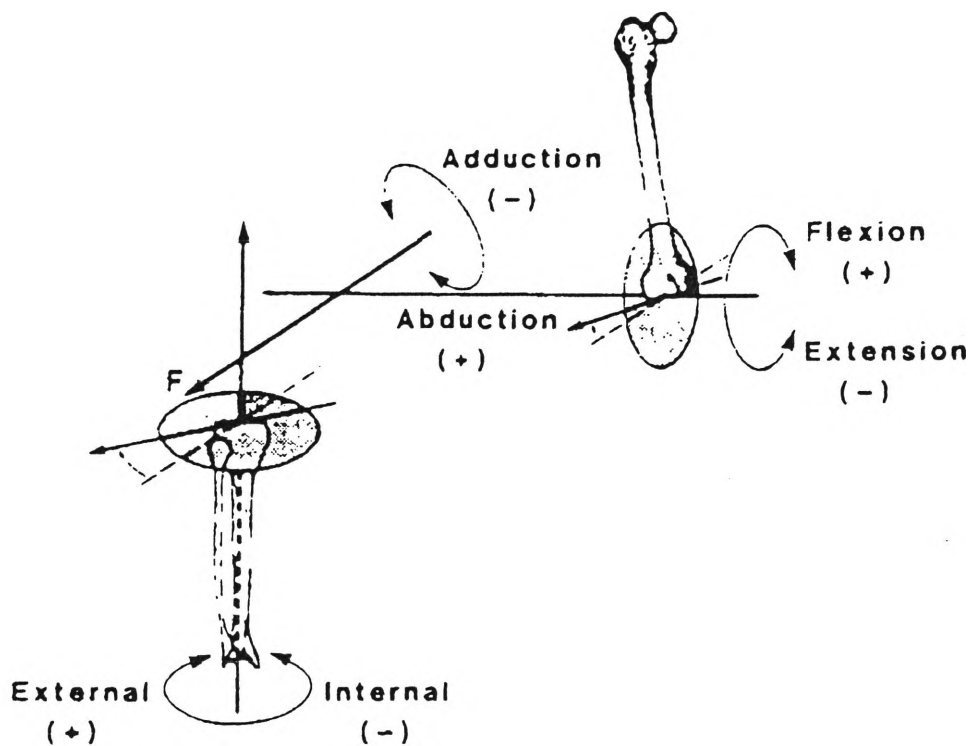


Figure 2.10: The Joint Coordinate System of Grood and Suntay (1983, p. 138).

If these rotations were defined as ϕ , φ , and θ respectively, this JCS would provide a general geometric representation of the Euler angles.

2.5 The DLT Filming Technique

In the analysis of general three-dimensional motion a single camera will not give accurate information (Walton, 1979; Woltring and Huiskes, 1990). Body fixed coordinates for at least three non-colinear markers allow full recovery of a rigid body's position if multiple cameras are used (Miller *et al.*, 1980; Woltring, 1980; Woltring and Huiskes, 1990).

The DLT method of three-dimensional motion reconstruction was used in this study for data transformation. This method established a direct linear relationship between comparator coordinates of points on two-dimensional photographic planes with the corresponding three-dimensional object space coordinates (Marzan and Karara, 1975). Filming procedures used prior to the development of the DLT method were dependent on the use of cameras with precisely known inner and outer parameters and fixed camera orientation and set-up for collecting accurate data (Abdel-Aziz and Karara, 1971; Shapiro, 1978). In the DLT method, camera positioning was completely free except that the optical axes of the cameras had to intercept one another (Van Gheluwe, 1974). The greater mathematical complexity of the DLT method allowed for these simpler filming procedures (Dapena, Harman and Miller, 1982).

The DLT filming technique is based upon calibrating the space in which the object or subject is to be filmed by firstly filming a set of control points of known spatial coordinates. There must be a minimum of six control points but it is generally recognised that a greater number of such control points yields greater accuracy in the data collection (Abdel-Aziz and Karara, 1971; Shapiro, 1978; Walton, 1979; Hatze, 1988). These control points are generally positioned on a rigid structure, usually a metal cube frame which is placed in the object space. After having been filmed, this frame can be removed and filming of the motion of interest can commence. Accuracy problems arise when any part of the motion occurs outside the calibrated space (Woltring, 1980; Dapena *et al.*, 1982; Wood and Marshall, 1986). However, in some situations a compromise must be made between accuracy of the calibrated space with a frame large enough to include the complete motion of interest and the practical implications of construction, transport and processing time involved when using a larger cube. Such large structures are also likely to be affected by stress deformation (Dapena *et al.*, 1982).

Walton (1979) described the construction of three-dimensional object coordinates from a combination of two-dimensional image planes. The DLT analysis used in this study will be based upon Walton's guidelines. Figure 2.11 shows n_x , n_y , and n_z as an orthogonal triad of unit vectors. These, combined with an origin (point A) define a three-dimensional reference frame fixed in the object space. All points in this object space have three dimensional coordinates (x, y, z) in relation to the object reference frame. Point O is one such point. A position vector P defines the position of point O with respect to point A.

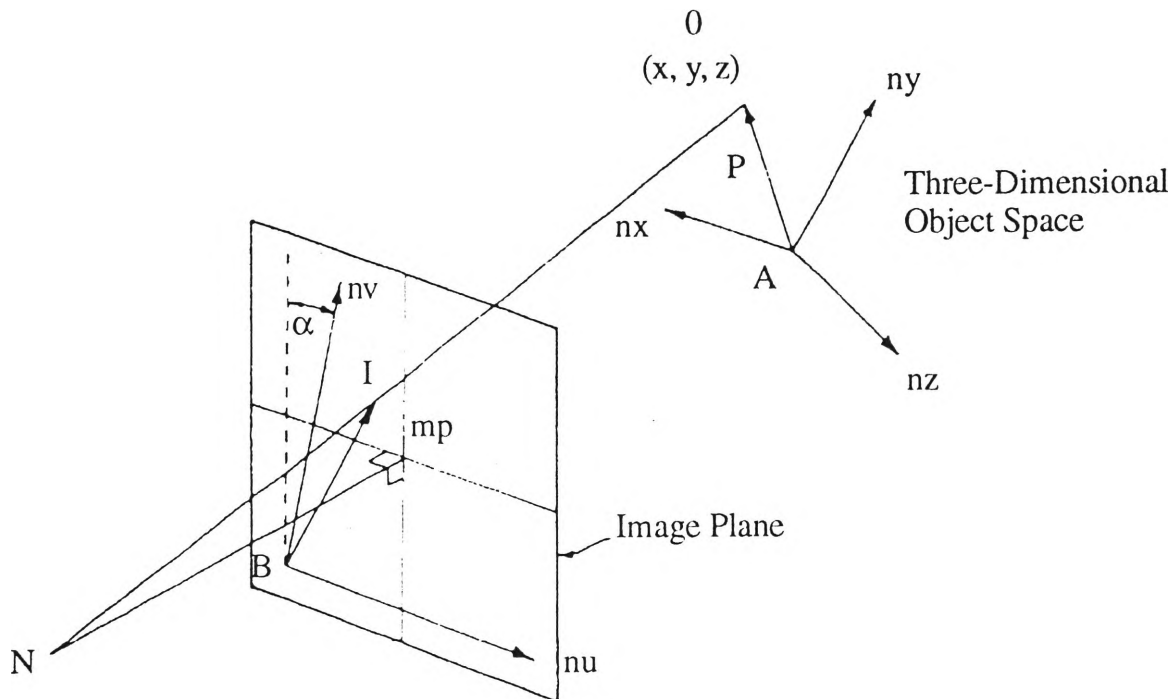


Figure 2.11: The transformation of two-dimensional image planes into three-dimensional space (from Walton, 1979, p.73).

The two dimensional image plane is defined by the non-parallel unit vectors n_u and n_v , which are not necessarily perpendicular (the angle off perpendicular is given in Figure 2.11 by α), and point B. Position vector \bar{P} is contained in the image plane and defines the position of point I (two-dimensional coordinates u and v) with respect to point B. However, the same point on a two-dimensional image does not represent a specific location in space, but rather a location on a specific plane in space (Edwards, 1992). Each camera

used will therefore provide its own two-dimensional coordinates of that point. If a point has the three-dimensional coordinates X, Y, and Z, and its image coordinates are u and v, and it has been filmed by the ith camera then the following matrix relationship will exist:

$$\begin{bmatrix} u - u_p \\ v - v_p \\ -C \end{bmatrix} = [M]\lambda \begin{bmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{bmatrix} \quad (4)$$

From Edwards (1992).

Where :

C = the principal distance

λ = the scaling factor

u_p and v_p = the coordinates of the principal point

$[M]$ = a 3 x 3 rotation matrix

X_o , Y_o , and Z_o = the three-dimensional coordinates of the camera perspective centre.

The object - image transformation is :

$$U = \frac{Ax + By + Cz + D}{Ex + Fy + Gz + 1} \quad (5)$$

$$V = \frac{Hx + Jy + Kz + L}{Ex + Fy + Gz + 1} \quad (6)$$

From Walton (1979)

Where :

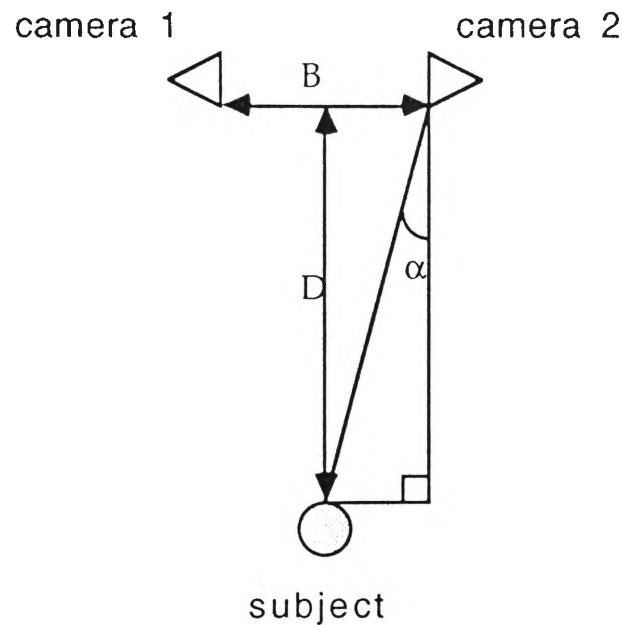
U and V = the two dimensional film coordinates, and

A - L = the 11 camera constants calculated by the DLT programme.

Equations 5 and 6 are known as the two DLT equations and are used on all the known control points. The minimum of six control points will yield a set of 12 equations to be solved for each camera. The equations are then solved for the 11 DLT constants. These 11 camera constants are uniquely determined by the DLT programme for the specific cameras, lenses, and camera set-up being used (Van Gheluwe, 1974; Marzan and Karara, 1975). These constants minimise the effects of the possible sources of error such as lens distortion, linear film deformation and comparator errors (Marzan and Karara, 1975; Dapena *et al.*, 1982). For further mathematical proof of the DLT reconstruction see Appendix A.

Black and Sprigings (1979) noted that of the major filming procedure errors of timing and asynchronisation, parallax (the apparent location discrepancy of an object when viewed from two different positions), scaling and perspective errors; perspective error was the major concern and has received the most attention. Martin and Pongratz (1974a, 1974b) devised equations to almost eliminate perspective error from three-dimensional film analysis but relatively rigid filming conditions were still necessary. Computer programmes have since been produced by Marzan and Karara (1975) and Hatze (1988) which have further reduced perspective errors. The optimal camera configuration is dependent upon the most effective camera - camera : camera - object distance ratio (Edwards, 1992). The accuracy of the DLT technique has been found acceptable when this ratio is between 1:1 and 1:3 (Hatzé, 1988) although there is some controversy concerning the most accurate ratio. Shapiro (1978) found that optimal data was obtained when this ratio was 1:3 and convergence kept to a minimum. Figure 2.12 is a diagrammatic representation of 1:2 camera base : object ratio and the angle of convergence.

Various authors have been interested in evaluating the accuracy of the DLT technique (Shapiro, 1978; Miller *et al.*, 1980; Wood and Marshall, 1986; Hatze, 1988; Kennedy, Wright and Smith, 1989) and all studies found accuracies within acceptable limits. Shapiro (1978) measured average accuracy of ± 0.5 cm in the location of spatial coordinates, and 1% to 4% deviation in the calculation of second derivatives (acceleration due to gravity). Many authors have also applied the DLT method to the biomechanical analysis of human motion, thus demonstrating its practicality, robustness and accuracy for such studies (Feltner and Dapena, 1986; Steele, 1988; Knudson, 1990; Neal, 1991). To the best of the authors knowledge, there have been no studies utilising the DLT technique on alpine skiing.



Where :

B = the distance between the centres of the bases of the two cameras,

D = the length of the perpendicular bisector of B connecting with the subject, and

α = the angle of convergence.

Figure 2.12: The camera base: object ratio in the DLT filming technique (adapted from Edwards, 1992).

2.6 Summary

The repetitive nature of impacts to the leg at varying segmental alignments encountered in competitive mogul skiing leads to many injuries to the lower limbs, especially to the ligaments of the knee joint. Although a number of possible mechanisms have been described in the scientific literature on general alpine skiing to account for knee injuries, no injury mechanisms in mogul skiing have been analysed. This study was designed to provide an extensive kinematic description of mogul skiing with the intention of identifying such possible mechanisms. This analysis will also be useful in the modification of the technique of elite mogul skiers for competition. As the motions involved in mogul skiing occur in more than one plane a three-dimensional analysis technique was necessary.

CHAPTER 3

METHODOLOGY

3.1 Statistical Approach and Subjects

Bates, Dufek and Davis (1992) stated that a minimum of 10 trials in conjunction with a sample size of five were necessary to obtain statistical power values of greater than 90% for all comparisons. The necessity of obtaining elite subjects for this study limited the sample size available at the time filming took place to three subjects and the aims of this study required no more than four trials per subject. Consequently the statistical approach adopted was the treatment of each subject as a case study (Leeder, 1984). This study was therefore a descriptive study as expressed by McLean (1984) based upon an open ended research approach outlined in Haddon, Suchman and Klein (1964).

All subjects were elite competitive mogul skiers. Subject 1 had skied on the Australian and United States national circuits and Subjects 2 and 3 on the World Cup circuit. Personal details are given in Table 3.1.

Table 3.1: Subject details.

Subject	age	yrs. competition	height (cm)	weight * (kg)
1	19	2	180	82
2	37	10	178	67
3	30	9	183	79

* weight includes ski boots and suits.

All subjects were required to be familiar with a subject information package and to complete a subject consent form (Appendix C) ensuring the procedures of this study satisfied National Health and Medical Research Committee (NHMRC) criteria.

3.2 Experimental Protocol

The task to be performed by each subject was one standard mogul turn on a reference mogul after a run in. The cameras were positioned so this motion occurred in the centre of their field of view so the complete turn could be analysed. To enable the three-dimensional analysis of the segments, external markers were necessary for the definition of x and y coordinates on the film planes.

All filming took place at Thredbo Alpine Village, New South Wales (NSW). A series of moguls was constructed to resemble a competition layout with the help and supervision of the Director of the NSW Freestyle Skiing Programme. This artificial mogul series was chosen in preference to existing mogul fields as it permitted filming and equipment location with minimum interference from skier traffic and also made it possible to position the moguls for the most advantageous camera positions. Five moguls were constructed, the last one being the reference mogul in the field of view of both cameras. The subjects started their trial approximately 10 m before the first mogul to reach a comfortable position relative to the mogul series and an appropriate velocity before initiating the turns. The first four turns then provided an opportunity to establish rhythm and technique before the turn on the reference mogul was executed. This final turn was filmed for subsequent analysis.

Impact was defined in this study as the time at which the base of the ski directly underneath the ski boot came in contact with the mogul.

3.3 Marker Positioning

The markers used in this study were 2.5 cm diameter polystyrene spheres attached to 1 cm concave plastic rods. The spheres when attached therefore protruded from the subject's body by 1 cm. Spheres were chosen as markers to ensure a consistent centroid position regardless of viewing angle. There was some error introduced in assuming the centre of the sphere's photographic image was the same point as the image of a geometrical point at the sphere's centre. However calculations have shown that this error was smaller than the resolution error of the manual motion analyser used in this study (Miller *et al.*, 1980).

The markers were painted various colours to enable differentiation from the subjects' suits in the subsequent film analysis. Two suits were used in this study, one FIS approved

downhill racing suit (used by Subjects 1 and 3) and one pair of skin tight racing pants with a tight sweater (Subject 2). Prior to the filming sessions marker positions were identified by attaching stickers on the suits while the suits were worn. The suits were then removed and the markers were attached to the suits using thumb tacks inserted from the reverse (inside) surface of the material in the positions identified by the stickers. Marker attachment proved to be very rigid and this method prevented loss of markers during the filming sessions. After the markers had been attached the subjects could again wear the suits. Where necessary minor adjustments to marker position were made immediately prior to the trials by manipulating the skin tight suits. Ski boot markers were attached directly onto the boot with highly adhesive double-sided carpet tape. See Figure 3.1 for an illustration of boot and leg markers.



Figure 3.1: Marker positioning on the leg and ski boot.

A minimum of three non-colinear markers are necessary to describe the position of a segment in three dimensions. In this study five markers were positioned on the feet, eight

markers on each leg and thigh and five on the torso. The redundant markers were used to accommodate for the loss of any markers due to the dynamic nature of the activity filmed and also to provide sufficient choice of markers to be digitised in the event of some being obscured from the camera views. The positions of the markers were chosen to satisfy two criteria :

- 1) Each marker should be visible in at least two cameras throughout the whole trial.
- 2) The markers should move as little as possible in relation to the anatomical position of the segment. They were therefore placed over prominent bone landmarks where possible and away from any large muscle mass which was likely to change the marker's position when contracted or relaxed. For exact positions of the markers chosen for analysis see Appendix D.

3.4 Calibration Cube Construction

A minimum of six points with precisely known x, y, and z coordinates in relation to an origin are necessary to calculate the 11 DLT parameters although it is well documented that a greater number of such control points will provide more accurate parameters. These points must be distributed so that the motion of interest occurs in the calibrated space . In this study a 2 m x 2 m x 2 m cube was constructed with 32 control points (Figure 3.2 and also Appendix F).

The cube was composed of 2 m aluminium rods of 12 mm diameter. Eight 5 cm aluminium blocks were positioned on the corners. Each block had three 12 mm holes for the positioning of the three intersecting rods, and three bolts on to which to attach the diagonal tension wires (see Figure 3.3).

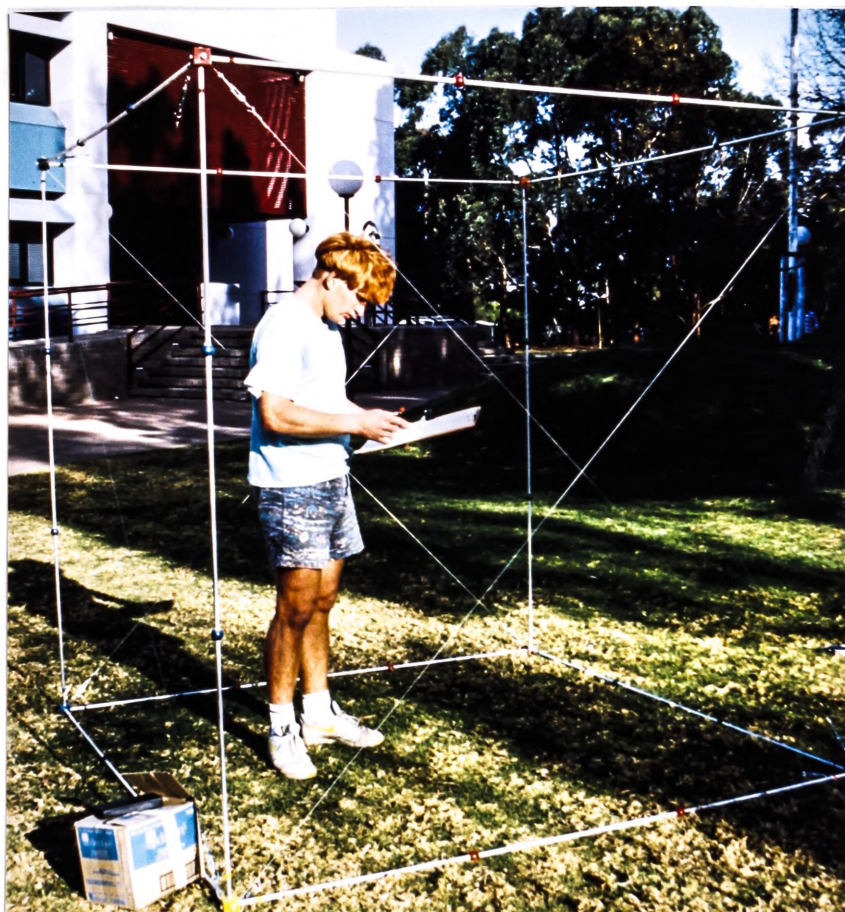


Figure 3.2: The calibration cube.



Figure 3.3: Calibration cube construction detail.

Once the rods had been positioned the wires could be tensioned to ensure rigidity of the structure and hence obtain the precise dimensions of the cube. This set-up allowed for quick erection and dismantling of the cube with a minimum number of people. The control points were of different colours to enable easier identification of the cube faces on the film. Twenty-four control points (2.5 cm diameter wooden balls) were glued onto the rods such that each rod was divided into three equal lengths. Spheres were used so the centre of the marker could be identified from any angle. The eight corner blocks were also colour-coded and used as control points. Appendix F describes the set-up and exact distances of the control points in the x, y, and z directions from the origin (the distal edge of the outside bolts on the black-painted corner block).

3.5 Filming Procedures

Three 16 mm pin registered LOCAM high speed cameras were used for filming of the motion. The camera speed was set at a nominal rate of 200 frames per second (fps) with a three factor shutter, providing an exposure time of 1/600 second. Two Kern-Paillard, 16 mm, 1:1.8 and one Canon T.V. 12.5-75 mm, 1:1.8 lens were used. Aperture settings of between $f = 11$ and $f = 22$ were used, depending upon the varying light conditions at the time of each trial. The cameras were located 10 m from the centre of the mogul and 8 m apart, thus approximating a 1 : 1 camera distance : base ratio. The field of view of all cameras was approximately 5 m. All trials were also recorded on a standard Panasonic VHS video camera. This was used to record the complete trials including 'run in' and 'run out' phases that were excluded from the field of view of the fixed high speed cameras. The cameras were positioned on Manfrotto tripods inserted in the snow until the legs were resting upon the solid ground surface beneath this. This prevented any movement of the tripods as a result of slipping or melting of the snow beneath the legs. The battery packs for the powering of the cameras were insulated to prevent the cold environment from causing any malfunction and they were also kept in plastic bags to exclude any moisture. The cameras were also protected from any moisture, however the cold had no detrimental effect on their functioning. The film used was Kodak 7251 high speed daylight film., ASA 400.

Filming was completed in two sessions; one for Subject 1, the second for Subjects 2 and 3. Prior to each filming session and again at the conclusion of each session, the calibration cube was positioned in the object space by placing the uphill edge on the ground surface

beneath the snow and the downhill surface on two metal cases, ensuring horizontal alignment of the bottom edges (Figure 3.4). The cube was filmed for approximately two seconds and then removed for the trials. Care was taken not to move the cameras at any stage after the cube had been filmed. This ensured the three-dimensional coordinates of the known marker positions remained constant for all trials within a filming session.



Figure 3.4: Calibration of the subject space.

One of the three LOCAM cameras malfunctioned during filming and later inspection of the camera revealed problems with the film take-up spool. The two operational LOCAM cameras were operated by a single switch providing a certain degree of synchronisation, however greater synchronising accuracy was obtained by having an event visible to both these cameras in the background (see Section 3.7.1). The cameras were started approximately two seconds before the subject executed a turn on the reference mogul to ensure the film had obtained the set speed of 200 fps for filming of the motion of interest. The cameras were stopped approximately one second after the turn on the reference mogul

had been executed. The subject was in the field of view for approximately 0.5 second per trial. Four trials of each subject were filmed.

3.6 Calculation of the Anatomical Frames of Reference

3.6.1 The Transformation Measurements

The calculation of the anatomical frames of reference (AFOR) for each of the segments required measurement of the distance of each of the three markers digitised per segment with respect to the origin of the respective AFOR. These origins were previously defined in this study as the proximal joint centres (JC) of each segment. In order to obtain the transformation measurements, three photographic slides were taken on an Olympus 35 mm camera of each subject prior to and after the trials. These slides were taken from anterior and both lateral views through 90° rotations, thus providing two images in the xy plane and one in the xz plane. A spirit level was used to ensure the camera was horizontal before each slide was taken (that is the film plane was vertical) and the shutter was released with a remote cable. A horizontal one metre scale reference was positioned directly behind the subject for each slide taken. The scale reference in each slide was to calculate scale factors to convert the measured units into real units. These scale factors ranged from 1.321 - 1.862 with a mean = 1.567. Two sets of slides were taken of each subject prior to the trials and one set was taken after the trials. There were therefore three sets of three slides for each subject giving a total of 27 slides.

These slides were projected onto a white-board. Distortion error was minimised by ensuring the projection axis of the slide was orthogonal to the white-board. The origin of the previously defined AFOR of each segment was marked on this image and the distance of the three markers was manually measured to the nearest millimetre in the locally defined x, y, and z directions (Figure 3.5).

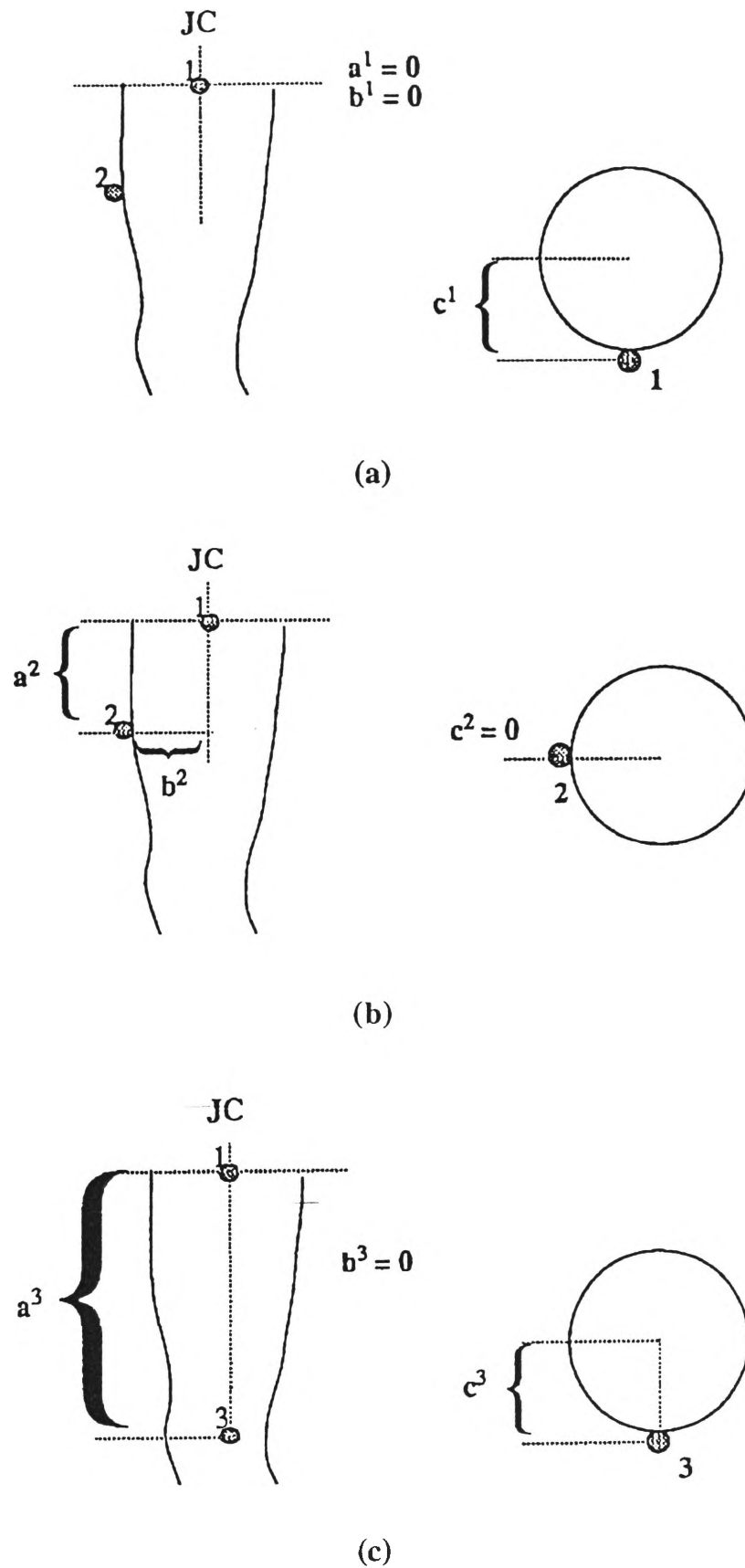


Figure 3.5: Transformation measurements for three markers on the thigh (from KinTrak User's Reference Guide 3.0, 1992, pp.4-4, 4-5).

3.6.2 Measuring Accuracy

It was assumed negligible marker movement occurred between the two photographic slides taken of each view of each subject prior to the trials as there was minimal subject movement at this stage, therefore the resulting measurements should be identical. Each measurement was taken to the nearest millimetre using a nylon measuring tape. The accuracy of the measuring procedure could be assessed by taking these transformation measurements twice off each of the 27 slides. The mean accuracy of measurements, calculated from the differences between measurements taken off the same slide, was ± 1 mm. The correlation coefficients for repeated measurements taken off the same slides are given in Table 3.2. Each value of r is for each set of three slides (one anterior and two lateral) taken.

Table 3.2: Correlation coefficients for repeated measurements.

Subjects	Slides	r
1	A	0.9986
	B	1.0000
	C	0.9998
2	A	0.9966
	B	0.9967
	C	0.9999
3	A	0.9998
	B	0.9999
	C	1.0000

The mean distance of each marker in the x, y, and z directions to the AFOR was then calculated for the measurements of each marker for all the slides prior to the trials and then for all the slides after the trials. The difference between these two mean values indicates the extent of the marker movement during the trials. Table 3.3 shows the mean value for these differences for the three markers on each segment for each subject.

Table 3.3: Marker movement (mm). Mean of each segment.

	Subject 1	Subject 2	Subject 3	mean	mean S1 , S3
<i>lf</i>	1	0.56	2.78	1.45	1.89
<i>ll</i>	5.11	14.78 *	3.78	7.89	4.45
<i>lt</i>	2.44	2.44	4.44	3.11	3.44
<i>rl</i>	3.33	9.00 *	2.11	4.81	2.72
<i>rt</i>	1.56	3.67	3.89	3.04	2.73
<i>t</i>	2.42	16	5.44	7.95	3.93
mean	2.64	7.74	3.74	4.71	3.19

Where :

lf is left foot,
ll is left leg,
lt is left thigh,
rl is right leg,
rt is right thigh, and
t is torso

* NB :

- 1) For Subject 2 marker movement on the left leg (*ll*) was 43.33 mm in the x direction; mean movement in the z and y directions was only 0.67 mm.
- 2) For Subject 2 marker movement on the right leg (*rl*) was 22.33 mm in the x direction; mean movement in the z and y directions was only 0.50 mm.
- 3) The large mean marker movements for *ll*, *rl* and *t* were biased by the large movements for one subject (Subject 2). All other marker movement was less across subjects and between marker locations.

The mean marker movement for all subjects was 4.71 mm and for Subjects 1 and 3 only 3.19 mm. These mean marker movement values indicate that the clothing worn by Subject 2 was not as suitable to minimise marker movement as that worn by Subjects 1 and 3. Unfortunately only one racing suit was available for this study. In order to minimise marker movement between trials subjects stopped skiing immediately after the completion of the trials and walked uphill to the starting position again. The motion of walking combined with the more dynamic skiing movements during each trial produced the observed marker movement. This procedure was however chosen in preference to the alternative of having the subjects ski to the nearest ski lift, catching the lift and then having to ski to the experimental set-up, as this would not only have involved more dynamic movement between trials but the ski lift would also have interfered with a number of the marker positions.

The length of each segment (defined by the AFOR as being the distance from the proximal to the distal joint centre) was also calculated twice on each slide both before and after the trials. As this measurement was a constant, any differences in these measurements must be attributed to measuring error. Table 3.4 shows differences in these measured values of segment lengths determined before and after the filming session.

Table 3.4: Differences in segment length measurements (mm), before and after each filming session.

	Subject 1	Subject 2	Subject 3	mean
<i>lf</i>	1	1	0	0.7
<i>ll</i>	0	1	2	1.0
<i>lt</i>	3	1	0	1.3
<i>rl</i>	2	0	1	1.0
<i>rt</i>	1	1	1	1.0
<i>t</i>	3	5	15	7.7
mean	1.7	1.5	3.2	2.1

Table 3.4 showed the measurements of the segment lengths of all subjects was measured to a mean accuracy of less than two millimetres with the exception of the torso of Subject 3. The torso length (mid-point of greater trochanters - mid-point of acromium processes) of all subjects was the least accurate. As opposed to the other relatively rigid segments the flexible nature of the vertebral column produces a certain variation in the length of the torso segment. This accounted for the 15 mm difference in the length of the torso for Subject 3. This value also increased the absolute mean value across segments from 1 mm (mean excluding torso value of 7.7 mm) to 2.1 mm.

The actual values used for the transformations were the means of the before- and after-positions as it could not be determined when (either in the series of trials or between trials) the marker movement had occurred. It was therefore assumed that the marker had this mean position throughout the whole series of trials. Also, as all trials were used in the analysis, the movement was assumed to be random across trials. Resulting mean data would reflect this random movement. The final mean figures used as the transformation measurements are shown in Appendix E.

3.7 Film Analysis

As previously mentioned (Section 3.5) one of the three LOCAM cameras malfunctioned during filming, the data collected by two cameras were therefore used for analysis purposes. Only two cameras are necessary for three-dimensional motion analysis and the malfunction of one camera therefore posed no problem. However, as both the functioning cameras were located on the subjects' left side, the elimination of one camera limited this study to an analysis of the left lower extremity and torso.

3.7.1 Digitising

The processed film was digitised by projecting the image onto a Graph Pen 8 sonic digitising screen (Science Accessories Corporation) with a Vanguard M-160W projection unit. The digitising screen was connected to an IBM compatible personal computer running the customised Digiplot software. This software collected the x and y coordinates of any point chosen on the screen and then provided editing facilities for the raw data.

Before each trial was digitised the cube position for that trial was digitised in three random frames. The average position of each of the control points was taken from these three frames. This minimised the effect of digitising error and any possible oscillation of the control points. By redigitising the cube before each trial even when the camera position had not changed, the effect of any minor movement of the digitising screen, the projection unit, or the film within the projection unit on the calibration of the object space was minimised. After digitising the cube the subject markers of each trial were digitised with no adjustment of the projection equipment.

Consecutive frames of each trial were digitised from a frame just prior to the point of maximum leg extension prior to the reference mogul to the completion of the turn on the reference mogul. This amounted to between 76 and 110 frames digitised per trial. Frames were synchronised between cameras by the first frame digitised being a certain number of frames before or after a background event visible in all cameras. This provided an estimated synchronisation error of less than two frames (± 0.01 seconds). Three non-collinear markers positioned on each segment were chosen for digitising based on being visible for most frames in each camera view. This provided the necessary three markers for the calculation of the three-dimensional position of each segment. Markers not visible in a certain frame were initially ignored and their position subsequently estimated as the midpoint of the preceding and following frames using the manual editing function in Digiplot.

Although the cameras were set at 200 frames/second the actual frame rate may vary from the manufacturer's specifications and from trial to trial. The precise time per frame (TPF) was calculated over the digitised period of each trial by using 0.01 second markers placed on the film during exposure :

$$\text{TPF} = \frac{0.01 \times \# \text{ marks}}{\# \text{ frames}} \quad (7)$$

This equation consistently gave a value of 0.005 seconds per frame for both cameras and all trials.

3.7.2 The Direct Linear Transformation (DLT)

A computer software package was developed to execute all DLT calculations including the accuracy determinations. This software was run on an AH 386 PC with a Compucon VGA display.

The U and V two-dimensional coordinates of the filmed calibration cube were averaged over the three frames in which the cube was digitised and these data together with the known coordinates of the control points on the cube were then input into the DLT equations to provide the 11 DLT constants of each camera.

The DLT constants and U and V coordinates of the calibration cube from both cameras were then used to calculate the predicted three-dimensional positions of the cube control points. The differences between these predicted positions to the measured real coordinates was an indication of the accuracy of the combined cube surveying, digitising and DLT technique. These distances were calculated as the x, y, and z components of the vector separating the predicted point and the measured control point. The total error for each point is then defined as the resultant vector distance (mm) of these three components:

$$Total\ Error = \sqrt{x^2 + y^2 + z^2} \quad (8)$$

The absolute mean error (AME) is the mean value of the total errors of all points per trial. The AME for every trial was less than 10 mm with a mean of 8.7 mm (see Table 3.5).

Table 3.5: Absolute Mean Error for each trial.

Subject/Tr.	AME (mm)
S1T1	9.2
S1T2	9.2
S1T3	8.6
S1T4	8.7
S2T1	9.5
S2T2	9.5
S2T3	8.0
S2T4	8.6
S3T1	8.3
S3T2	8.0
S3T3	8.5
S3T4	8.4
mean : 8.7	

Another assessment of experimental accuracy was the evaluation of predicted positions of the control points in two dimensions for both cameras. This provided predicted digitised U and V units which could be compared to the actual digitised coordinates. An example of the complete DLT programme output is shown for Subject 3 Trial 2 in Appendix B. After assessing these errors for each control point, any points with poor accuracy values could be discarded for recalculation of the 11 DLT coefficients thus ensuring greater accuracy in the ensuing calculation of the x, y, and z coordinates of the subject markers.

The three-dimensional spatial coordinates of the markers positioned on the subjects were calculated with the input of the DLT constants and x, y coordinates of each marker in both cameras. This provided an output of x, y, and z coordinates of each marker for each frame throughout a complete trial. These resulting coordinates were formed into file formats capable of being read into the Motion Analysis Corporation (MAC), Sun Unix ExpertVision (EV) system operating on a SPARC station IPC. These files were separate

path files for the x, y and z coordinates that could be reformed into EV path files and then united into one file representing the complete paths for all markers throughout each trial. In order to have access to the KinTrak analysis software (see Section 3.9), random video and calibration data had to be collected through the Motion Analysis System (MAS). This was done at a the maximum frame rate accepted by EV of 60 frames per second. These data were collected for 1.66 seconds to simulate 100 frames of data collected on high speed film. These video and calibration data were then used as a template for the data of interest which required no further calibration as this was already accounted for in the DLT calculations. Once these random data had been collected in KinTrak EV permitted the formation of the x, y, z path trial into a file which KinTrak would accept for analysis.

The track/edit section of EV included a running mean data smoothing function which was applied to the path of every marker through all frames for the x, y and z coordinates separately. This smoothing technique allocated a value to the current point which was a weighted average of itself and its neighbours. The weights used were normally distributed about the current point with the maximum weight given to the central element and increasingly smaller weights for elements increasingly distant from this central element.

3.8 The Three-Dimensional Kinematic Analysis

3.8.1 Calculation of the Angles

The KinTrak three-dimensional analysis software package was used in this study to perform the calculations of transformations of the coordinate systems and of the kinematic variables defined in Section 1.3.

As previously described an axis system was formed in a segment using three named points. As defined by the KinTrak software the x axis of the local coordinate system connected the proximal point to the distal point, using the proximal point as the origin. The three points form a plane in which the y axis will lie in the direction of the third point. The z axis was then determined by the right-hand coordinate system. The transformation measurements (Section 3.6) permitted the translation and rotation of this axis system to a biomechanically meaningful position (Figure 3.6).

The analysis of the segment angles through definition of the segments by three points was a technique chosen for this study as it presented the opportunity to describe internal/external rotation of the segments in relation to each other. This is not possible in a three-dimensional analysis of segments defined simply by proximal and distal joint centres. A limitation of the definition of segments for three-dimensional analysis by two points was that the three-dimensional joint centre was impossible to mark externally. An external marker positioned on the greater trochanter, for example represented the hip joint centre in both the y and z directions but was a considerable distance in the x direction from the hip joint centre. However, for segments in this study for which proximal and distal joint centres were approximated by markers, the two point segment analysis of flexion/extension or abduction/adduction was possible (see Section 4.2.2).

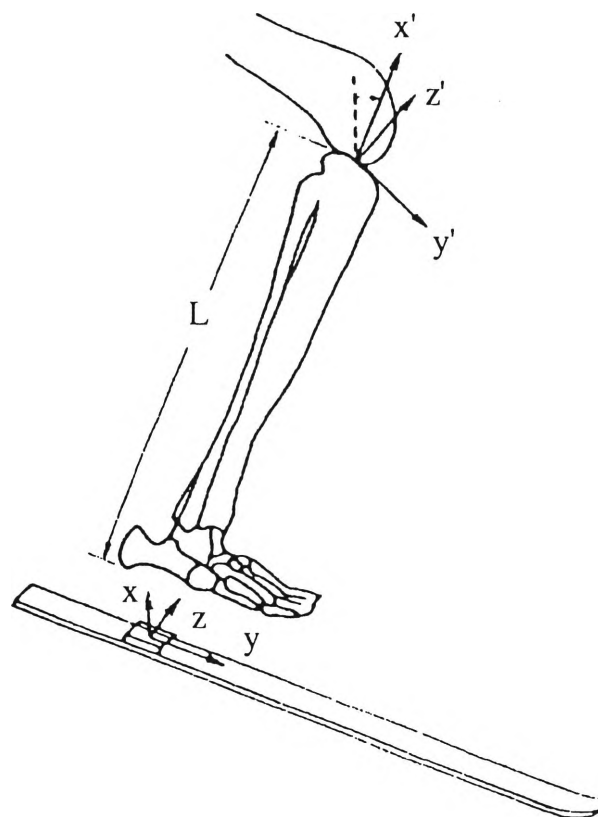


Figure 3.6: The orientation of local coordinate systems (adapted from Maxwell and Hull, 1989, p.237).

The joint coordinate system (JCS) used by KinTrak in order to permit three independent rotations to describe flexion/extension, abduction/adduction and internal/external rotations

required the definition of two axis pairs and the angle of interest. The axis pair for a segment denotes the hinge (or 'principle' axis of rotation) and the long axis of that segment. In this study the first segment was always the segment proximal to the joint of interest and the second segment was the joint distal to the joint of interest. When the hip was the joint of interest, the torso was considered as the first segment and the thigh as the second. The angle of interest chosen was one of the following :

- 1) Hinge : rotation of the second segment about the hinge axis of the first segment.
- 2) Cross : rotation of the second segment about the axis defined as the cross product of the first segment hinge axis and the second segment long axis.
- 3) Long : rotation of the second segment about the long axis of the second segment with reference to the first segment.

The JCS angles were calculated as follows (KinTrak User's Reference Guide 3.0, 01/92) :

F_1^j = the direction cosine matrix for the first segment $i, j = 1, 2, 3$

S_1^j = the direction cosine matrix for the second segment $i, j = 1, 2, 3$

$h1 = F_{h1}^1 i + F_{h1}^2 j + F_{h1}^3 k$ where $h1 = 1, 2, 3$
= hinge axis of first segment.

$l1 = F_{l1}^1 i + F_{l1}^2 j + F_{l1}^3 k$ where $l1 = 1, 2, 3$
= long axis of first segment.

$h2 = S_{h2}^1 i + S_{h2}^2 j + S_{h2}^3 k$ where $h2 = 1, 2, 3$
= hinge axis of second segment.

$l2 = S_{l2}^1 i + S_{l2}^2 j + S_{l2}^3 k$ where $l2 = 1, 2, 3$
= long axis of second segment.

(9)

Where : i, j and k are unit vectors in the direction of the global coordinate system.

$$\begin{aligned}
 a &= l1 \times h1 \\
 s &= l2 \times h2 \\
 e &= l2 \times h1
 \end{aligned}$$

If $e \cdot s < 0$, then the direction of e is reversed.

$$r = h1 \times e$$

(10)

$$\text{hinge angle} = \arccos \frac{a \cdot e}{|e|}$$

If $e \cdot l1 < 0$, then direction of hinge angle changes.

$$\text{long angle} = \arccos \frac{s \cdot e}{|e|}$$

If $e \cdot h2 < 0$, then direction of long angle changes.

$$\text{cross angle} = \arccos \frac{l2 \cdot r}{|r|}$$

If $h1 \cdot l2 < 0$, then direction of cross angle is reversed.

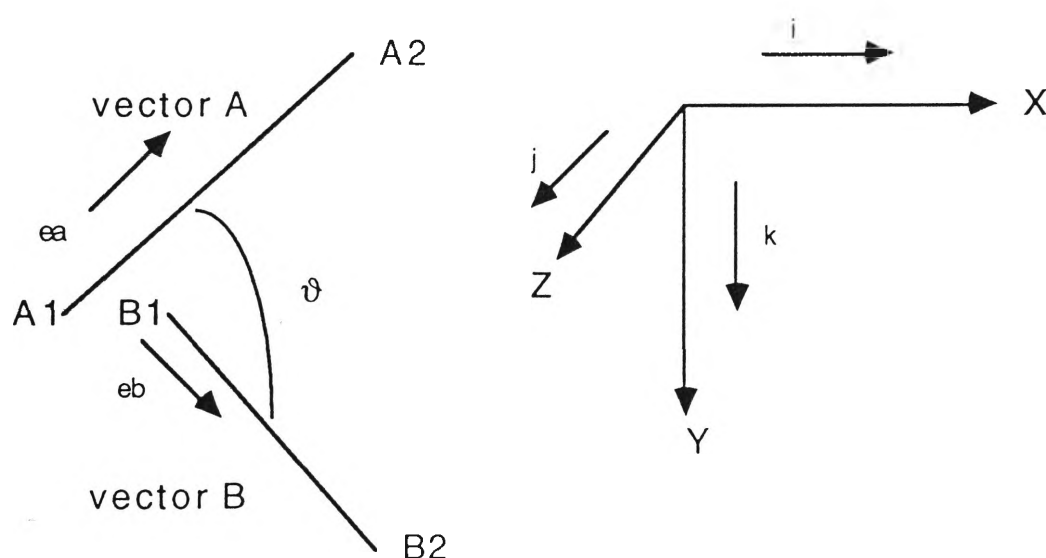
(11)

The variables chosen in KinTrak for the calculation of these angles to represent biomechanically significant motions are shown in Table 3.6.

Table 3.6: Joint Coordinate System variables chosen for KinTrak.

Joint	Angle	Motion	h1	l1	h2	l2
ankle	hinge	dorsi/plantar flexion	Z	X	Z	Y
	cross	abduction/adduction	Z	X	Z	Y
knee	hinge	flexion/extension	Z	X	Z	X
	cross	varus/valgus	Z	X	Z	X
	long	internal/external rotation	Z	X	Z	X
hip	hinge	flexion/extension	Z	X	Z	X
	cross	abduction/adduction	Z	X	Z	X
	long	internal/external rotation	Z	X	Z	X

Furthermore the absolute angle of each joint could be calculated throughout each trial as described in Figure 3.7.

**Figure 3.7:** The calculation of the absolute angles.

Where:

$$ea = (ea_x i) + (ea_y j) + (ea_z k) \quad (\text{unit vector}) \quad (12)$$

$$ea_x = \frac{A1_x - A2_x}{|A|} \quad (13)$$

and where:

$$|A| = \sqrt{(A2_x - A1_x)^2 + (A2_y - A1_y)^2 + (A2_z - A1_z)^2} \quad (14)$$

then:

$$ea \cdot eb = |ea||eb|\cos\theta$$

and therefore:

$$\theta = \arccos(ea \cdot eb) \quad (15)$$

In order to calculate an absolute angle, reference axes for the two segments of interest had to be nominated. These were :

- absolute angle; ankle : Y (foot), X (leg),
- absolute angle; knee : X (leg), X (thigh),
- absolute angle; hip : X (thigh), X (torso).

The calibration of the subject space by filming the cube and calculating the DLT parameters defined this space in relation to relatively standard (for example force plate conventions) global axes. KinTrak however defined the local coordinate systems in a different orientation for the calculation of the angles of rotation between the body segments. When comparing the absolute angle of a body segment to the global frame of reference different axis orientations were therefore employed. These relative orientations were as follows :

- 1) Global positive x direction relates to local positive y direction.
- 2) Global positive y direction relates to local positive z direction.
- 3) Global negative z direction relates to local positive x direction for the foot, leg and thigh, and to the local negative x direction for the torso.

3.8.2 Interpretation of Angular Values

Explanation of JCS angles :

Ankle : flexion/extension : positive 90° = upright standing,
dorsiflexion as angle approaches 0° .

Knee : flexion/extension : 0° = full extension,
flexion as angle becomes more positive.
abduction/adduction : 180° = no abduction or adduction,
abduction as angle approaches 0° .
internal/external rotation : 0° = no internal/external rotation of leg relative to
thigh,
internal rotation = positive,
external rotation = negative.

Hip : flexion/extension : 0° = full extension (upright posture),
flexion as angle becomes more negative.
abduction/adduction : -180° = no abduction or adduction,
adduction as angle approaches 0° .
internal/external rotation : as for knee.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The small subject number used in this study meant that any differences or similarities shown between trials and subjects could only be seen as trends and not be compared for statistical significance (see Section 3.1). The value of this study as applied to mogul skiing was therefore as a descriptive analysis. The majority of this chapter was concerned with the analysis of angular values across the ankle, knee and hip joints to describe trends in variation or similarity of these variables between trials. The data obtained in this study for Subjects 1 and 3 were more consistent and realistic than those of Subject 2 as a result of the more appropriate suits worn by Subjects 1 and 3. The results presented were therefore predominantly of Subjects 1 and 3 and Subject 2 data were only included where comparisons between subjects were made. The major trends shown in this study were demonstrated by Subject 1 data and specific trials of other subjects were provided to illustrate exceptional aspects of the motion.

The two operational cameras were positioned at an angle of 55° to each other, both viewing the left side of the subjects throughout the trials. Although the laterally positioned markers on the left side of the subjects were consistently visible in both operational cameras, those on the right foot, leg and thigh were often not visible for up to 30 consecutive frames. The markers on the right side were included in this study (see Appendix D and Appendix E). However the kinematic data obtained from using these were generally not able to be interpreted. The context of the methodology of this study therefore limited the presentation of results to the left foot, leg and thigh and torso.

4.2 Skiing Technique

The kinematic analysis of elite sports performers involved in their specialist event provided the possibility of a detailed definition of the characteristics of individual techniques and the identification of motions that would permit both a more effective execution of the mechanical purpose of the task and also a more aesthetic execution of the event. This is of particular importance in a sport such as mogul skiing in which competitors are judged upon their style as well as speed.

4.2.1 Angles at the Ankle

By calculating the absolute angle across a certain joint and comparing this to a specific JCS angle, an indication was obtained of the contribution of this JCS angle to the absolute angle. The modern, rigid ski boot was designed to limit motion of the foot relative to the tibia in any direction other than dorsi- or plantarflexion. It was therefore assumed that the absolute angle at the ankle joint was due almost exclusively to flexion/extension movements. A comparison of the absolute angle and the JCS angle of flexion/extension at the ankle for Subject 1, Trial 1 (S1T1) is given in Figure 4.1. as an example of the motions permitted at the ankle by the modern ski boot. (Trials were identified in this study by subject number followed by trial number of that subject. For example the first trial of Subject 1 was identified as Subject 1, Trial 1: S1T1).

The absolute angle shown in Figure 4.1 was of the foot -y axis to the leg +x axis and absolute angles greater than 90° therefore denoted greater flexion as opposed to the JCS angle where angles less than 90° denoted greater flexion. An angle of 90° indicated the standard anatomical posture at the ankle for both forms of calculation of the angle. As expected the two curves were almost precise mirror images across a line drawn at 90° which indicated minimal contribution to the absolute angle at the ankle from any rotations other than flexion/extension. The range of motion at the ankle in the ski boot in this trial was shown to be approximately 35° . The most extended position as indicated by the JCS flexion/extension angle was 80° (as compared to a corresponding dorsiflexion angle for the ski boot of 70° cited by Hauser and Schaff, 1987) and the least extended position 45° . Impact of the ski boot with the mogul for Subject 1, trial 1 was at time 0.185 s and Figure

4.2 indicated that 0.025 s later the extending movement was terminated and slight flexion occurred, possibly as a result of the impact.

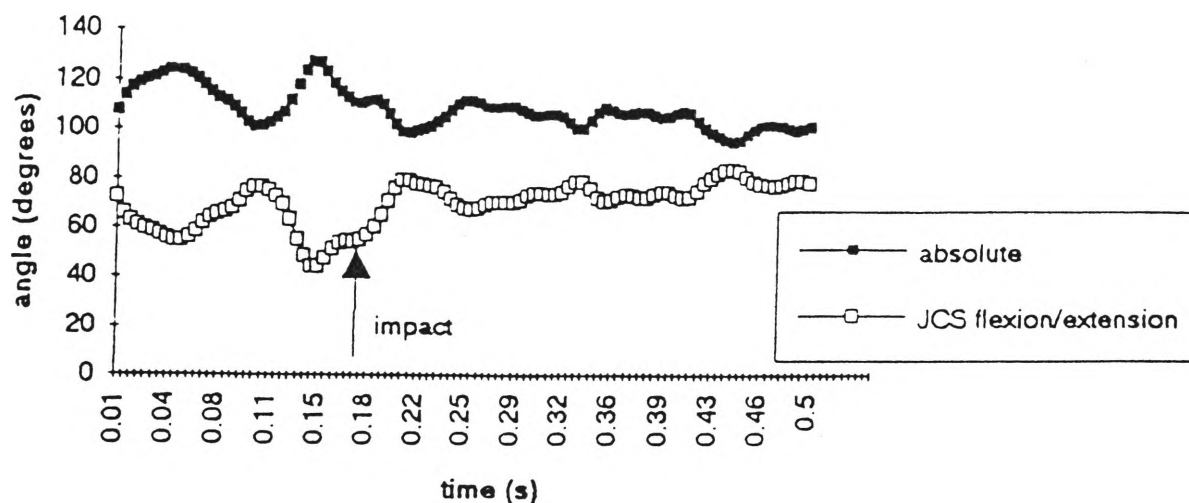


Figure 4.1: Comparison of absolute angle and JCS flexion/extension at the ankle joint for SIT1.

4.2.2 Angles at the Knee

As previously described (see Section 3.8.1) angles of flexion/extension and abduction/adduction could be described in a three-dimensional analysis for segments defined by proximal and distal joint centre markers. Figure 4.2 compared the results of an analysis of knee flexion/extension for SIT1 as both a JCS angle between three point segments with transformation measurements and as a JCS angle between two point segments defined by proximal and distal joint centre markers (see Appendix D and Appendix E).

In Figure 4.2 the two curves lay close to each other indicating the same pattern of flexion/extension at the knee joint. However, the three point segment method can be regarded as more accurate due to its more precise definition of the segments in three-

dimensional space. These graphs showed greatest extension at the knee joint occurred at time 0.075 s whereas impact (0.110 s later) occurred during a consistent flexing motion, apart from a short phase of extension occurring at impact and presumably as a result of impact. However, as opposed to the flexion/extension at the ankle (Figure 4.1), impact appeared to have less effect on the knee flexion/extension during the same trial.

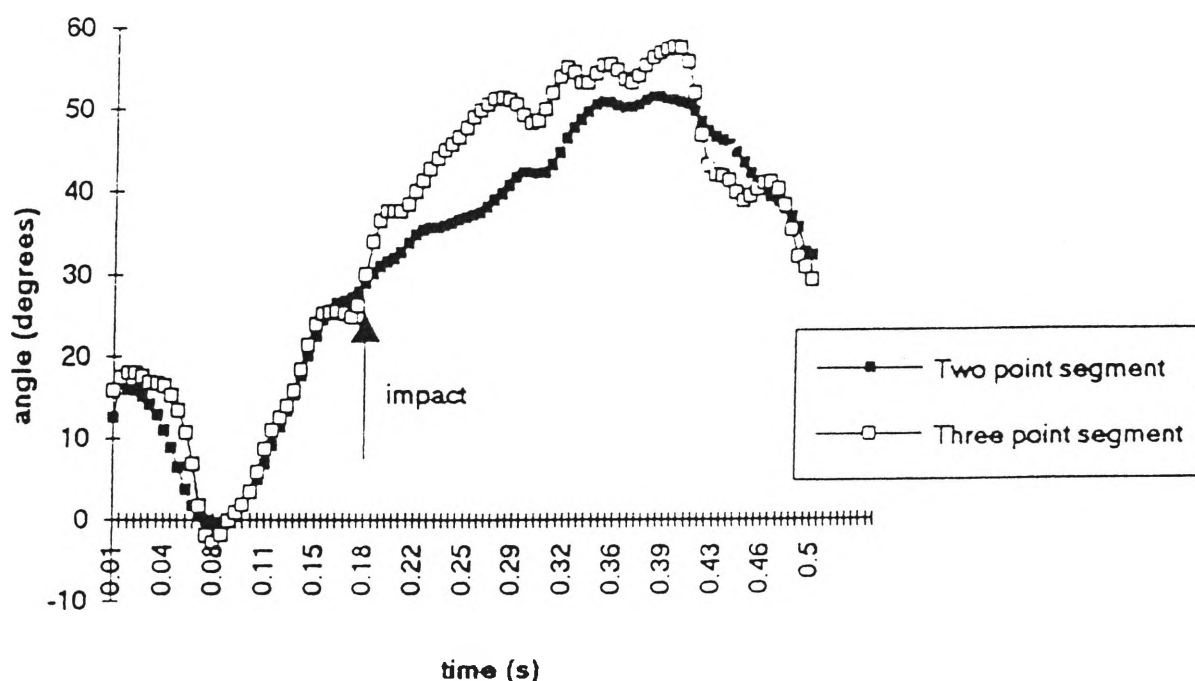


Figure 4.2: Comparison of SIT1 knee flexion/extension for segments defined by two and three points.

It was seen as fundamental to this study to provide a full description of the three-dimensional motion across the individual joints. This involved the analysis of all three rotations (flexion/extension, abduction/adduction, and internal/external rotation) throughout a complete trial for both the knee and the hip joints. The malfunction of one camera resulted in the two operational cameras being located towards one side of the motion being executed. Any three-dimensional analysis limited to two cameras will be severely limited in its determination of angles of internal/external rotation. The rotations occurring approximately in the plane of the subjects' motion (that was flexion/extension) were therefore most accurately calculated while the angles of internal/external rotation and

abduction/adduction could be used to describe trends but the actual values obtained were of a far lesser accuracy. The range of motion of a knee of a non-pathological subject would be far less (maximum of approximately 10°) about these two axes than some of the values provided in this study. The knee was primarily considered as a hinge joint rotating about the flexion/extension axis and the flexion/extension data were therefore considered the most important in this study.

The increased range of motion observed in the results of this study were presumably the result of the two camera experimental set-up providing little differentiation in the rotations of internal/external rotation and abduction/adduction between the knee and the hip. The hip, being a ball and socket joint was far more mobile through more degrees of freedom than the knee and in the present study motions occurring at the tibia were presumably not sufficiently isolated from those of the femur. The basic trends observed in the angles of rotation of internal/external rotation and abduction/adduction at the knee were considered in this study even though the actual values of these rotations could not be.

Figure 4.3 was an illustration of the angular values of the three rotations at the knee joint for S1T3 illustrating a range of motion in the angle of abduction/adduction at the knee of 40° (between 100° and 140°) throughout the trial. As explained above this was an unlikely range of motion for the knee of a non-pathological subject. However the trend could be seen that the knee was constantly abducted and there appeared to be minimal variation in the angle being shown as a result of the turning motion or of the undulation in the terrain caused by the mogul. The flexion/extension angle showing a range of motion of 85° (5° - 90°) described a similar pattern to that of S1T1 (Figure 4.2) with the subject almost fully extended after the pre-reference mogul and then flexing in the approach to the reference mogul. However in this trial the subject showed a more pronounced phase of extension as a result of impact than that illustrated in Figure 4.2. The range of motion in the angle of internal/external rotation of 135° (-40° - 75°) was obviously exaggerated, however it was interesting to note that the flexion/extension and internal/external rotation curves followed each other closely throughout the complete trial. Although the magnitude of the rotations about the internal/external rotation axis were too large, Figure 4.3 showed that increased flexion was accompanied by greater internal rotation and increased extension by greater external rotation.

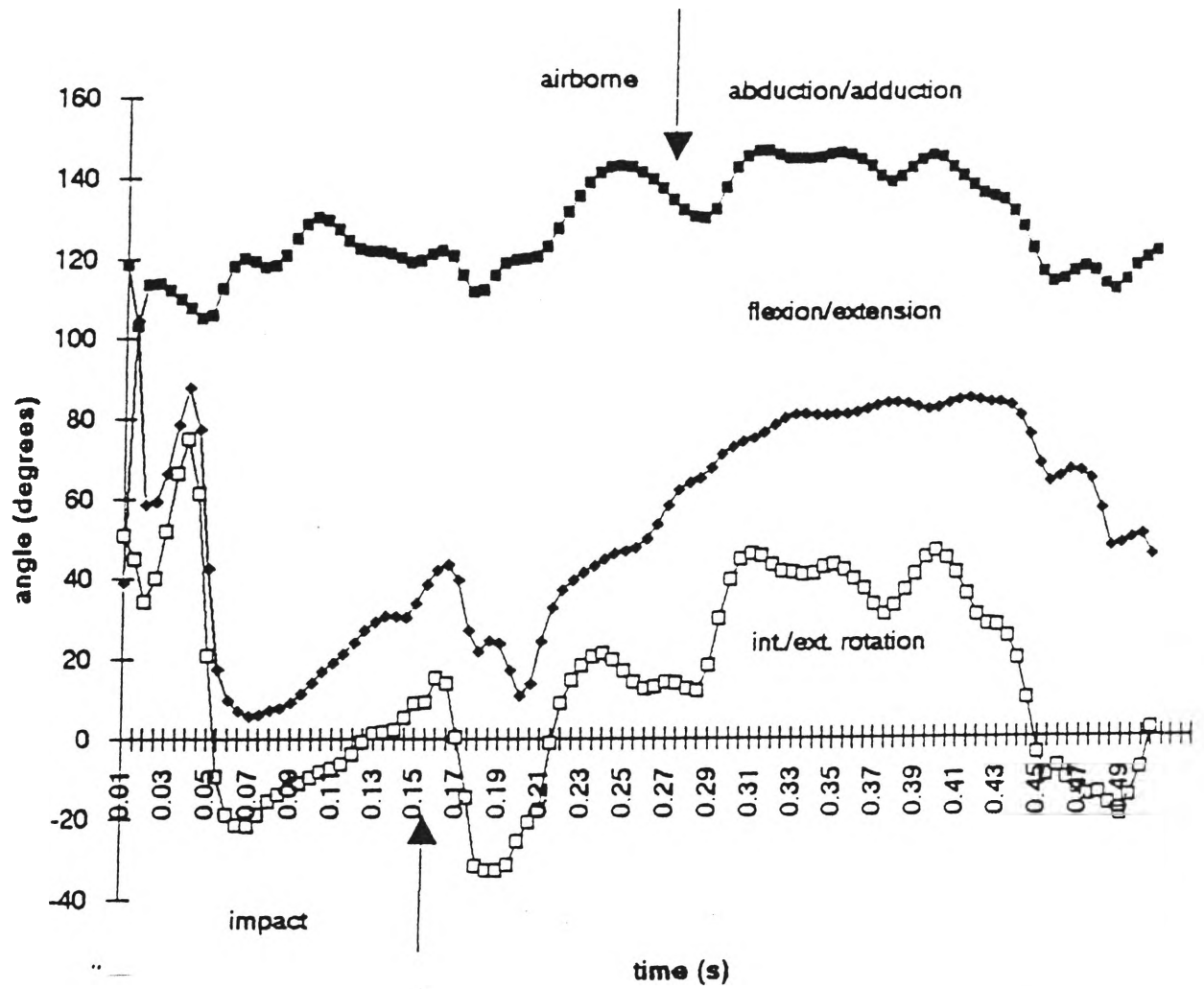


Figure 4.3: All rotations at the knee joint for S1T3.

The two curves in Figure 4.4 again closely resembled each other which indicated a close relationship between internal/external rotation and flexion/extension motions at the knee.

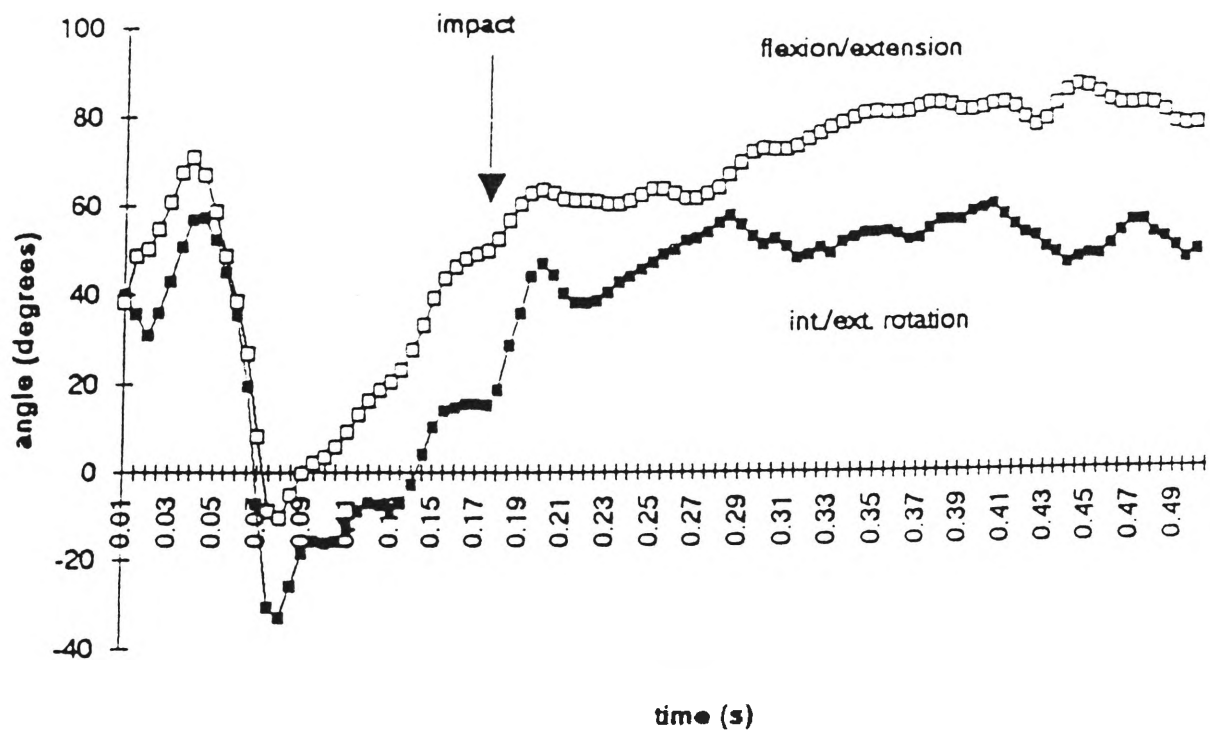


Figure 4.4: Combination of internal/external rotation with flexion/extension at the knee for S1T1.

The analysis of angles at the knee joint to this point has concentrated upon trials executed by Subject 1 to provide indications of the motions that occurred. However similar motions across the knee joint were exhibited by all subjects. Figure 4.5 provides a comparison of sequences of internal/external rotation among subjects.

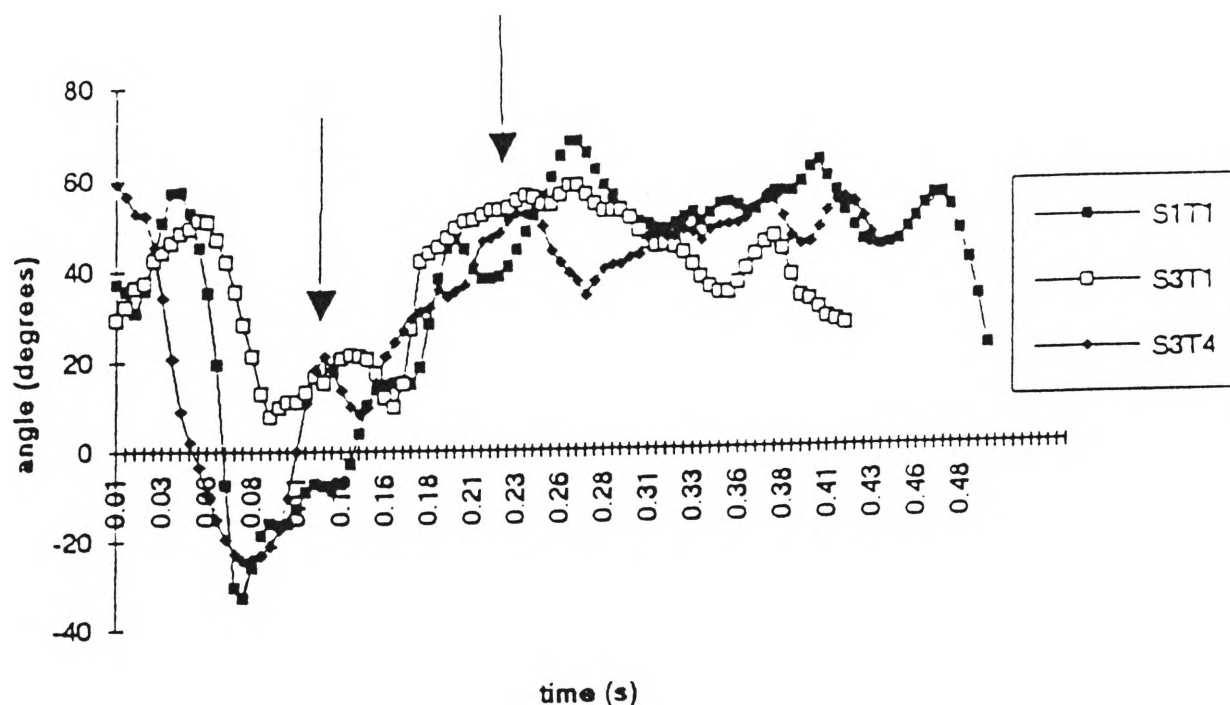


Figure 4.5: Comparison of internal/external rotation at the knee across three trials.

The two arrows indicated the approximate phase across all three trials in which the subjects were actually negotiating the reference mogul (from the time at which impact occurred to immediately prior to becoming airborne). In interpreting this graph it must be noted that although it provided a good indication of similarities in this variable, the times of impact and leaving the ground were different for each trial (see Appendix G). The arrows were therefore only an approximate indication of the times at which these two events occurred in the three trials. As in Figures 4.3 and 4.4, these trials illustrated a sequence of internal/external rotation at the knee with consistently increasing internal rotation during the phase of the turn in which the mogul was being negotiated with the least internally rotated phase of the turn being at approximately the same time as impact. The only time this figure indicates the subjects as having externally rotated tibia relative to the femur was immediately prior to impact. As mentioned previously the limitations of this study did not permit an analysis of the exact angles of these rotations but the trends observed provided an interesting indication of the motions employed by the subjects in the negotiation of the mogul.

4.2.3 Angles at the Hip

All angles of rotation at the hip were also analysed to show three-dimensional orientations of the thigh relative to the torso throughout trials. As an example, the graphs resulting from the analysis of rotation at the hip for SIT4 were presented in Figure 4.6.

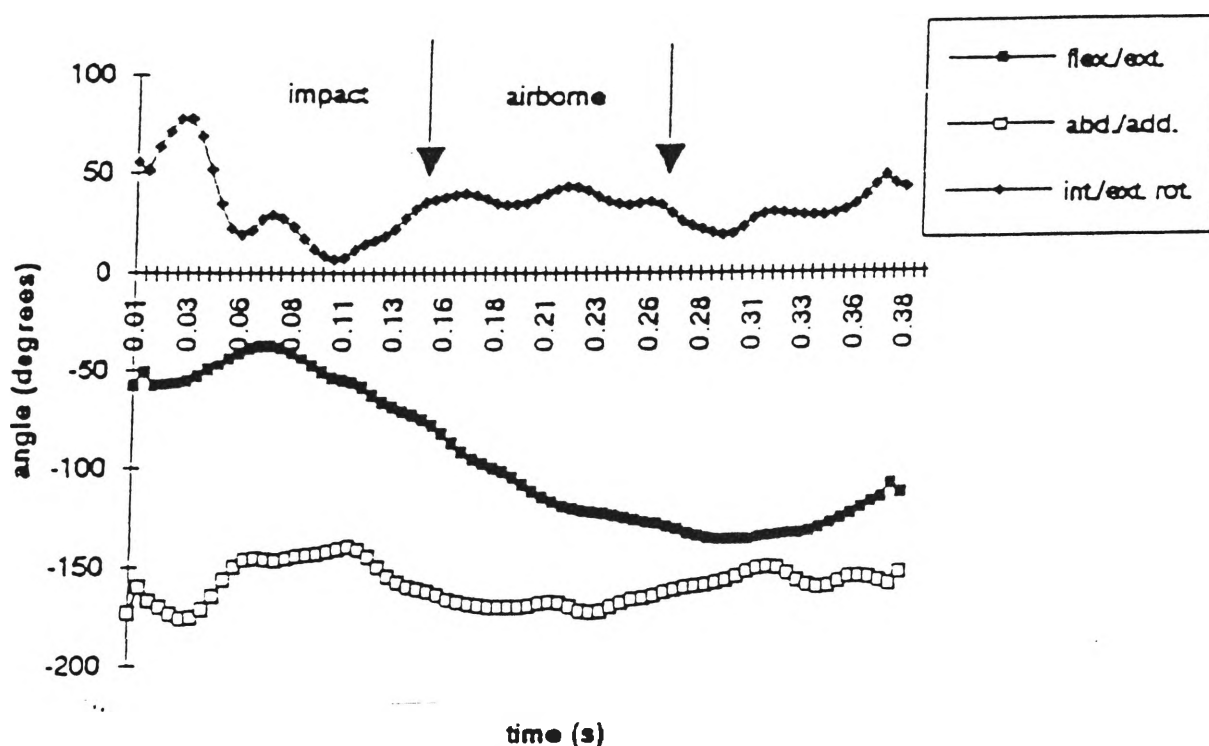


Figure 4.6: All rotations at the hip joint for SIT4.

In Figure 4.6 the angle of abduction/adduction was again the most consistent angle. This ranged from -150° to -175° indicating a relatively steady angle of abduction throughout the executed turn. As opposed to the knee, the angles of internal/external rotation and flexion/extension at the hip did not appear closely related. Apart from rotating towards a neutral internal/external rotation position prior to the reference mogul (from 75° to 10° , between times 0.025 s and 0.100 s in Figure 4.8) the hip was at a steady angle of internal rotation at the time of impact (35° with impact at 0.155 s). This Figure 4.6 showed a

pattern of internal/external rotation at the hip which appeared similar to that of the knee in other trials of Subject 1. The assumption made previously that the magnitude of the angle of internal/external rotation at the knee was influenced by the motions at the hip therefore appeared justified. The major range of motion at the hip occurred through flexion/extension and a consistent pattern of hip flexion/extension was seen in most trials.

As would be expected of elite competitors in any sport, the manner in which they execute their event should be consistent. This was demonstrated in Figure 4.7 which illustrated the hip flexion/extension angle through all trials executed by Subject 3.

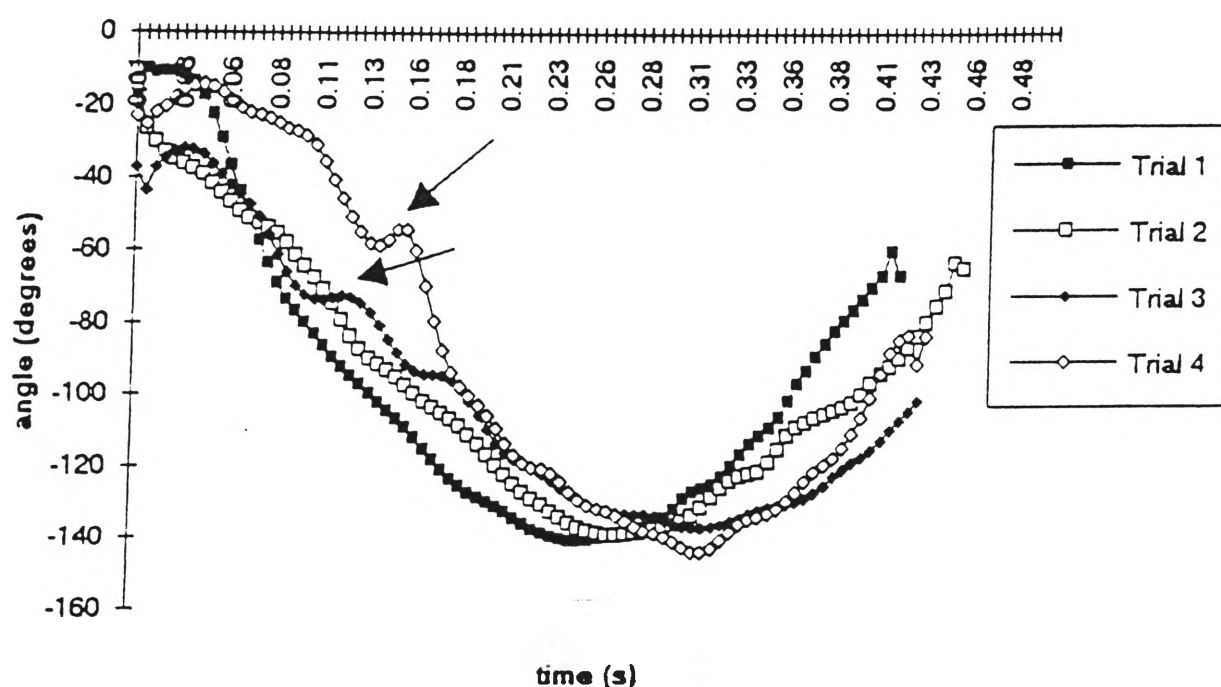


Figure 4.7: Subject 3, comparison of hip flexion/extension in all trials.

The arrows on this graph indicated a phase in the turn for trials 3 and 4 at which the angle at the hip became slightly more extended immediately after impact. Impact was at times 0.110 s and 0.075 s; the increased extension occurred at times 0.130 s and 0.095 s for trials 3 and 4 respectively. This was possibly a phase of passive extension at the hip as it may not have occurred as a result of muscle activity but solely through external forces. This position may possibly have represented a vulnerable position for the skier as identified

in the literature and this possibility is further explored in Section 4.3.1. Apart from the oscillation of the curves for trials 3 and 4, Subject 3 showed consistent patterns of hip flexion/extension throughout all trials.

4.2.4 Identification of the Carving Technique

It was assumed that the carving technique involved greater knee and hip angulation in order to increase the length of the edge in contact with the snow surface as opposed to a more vertically aligned posture in the wriggling technique where only a minimal length of the skis' edges are utilised (Hurn, 1990). The kinematic description of knee and hip angulation was by the calculation of the JCS angles of abduction/adduction at these joints (Figure 4.8).

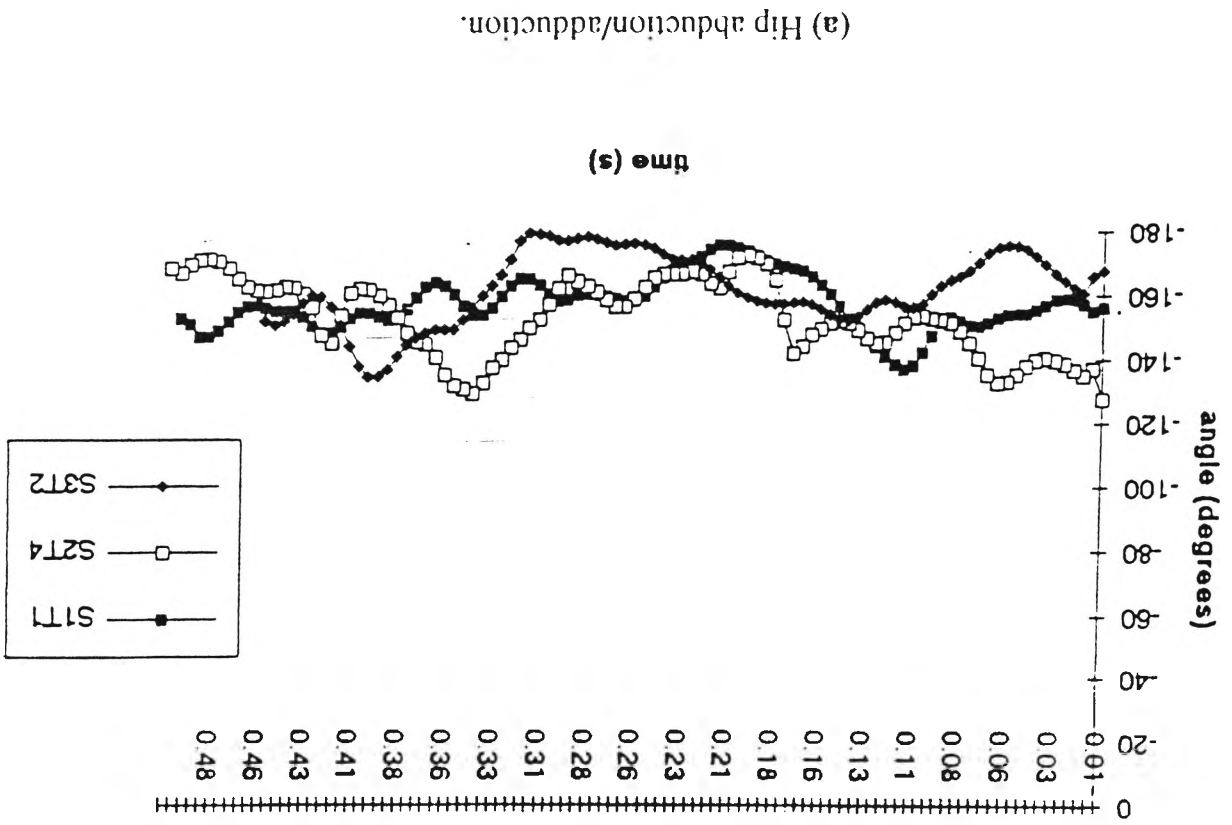
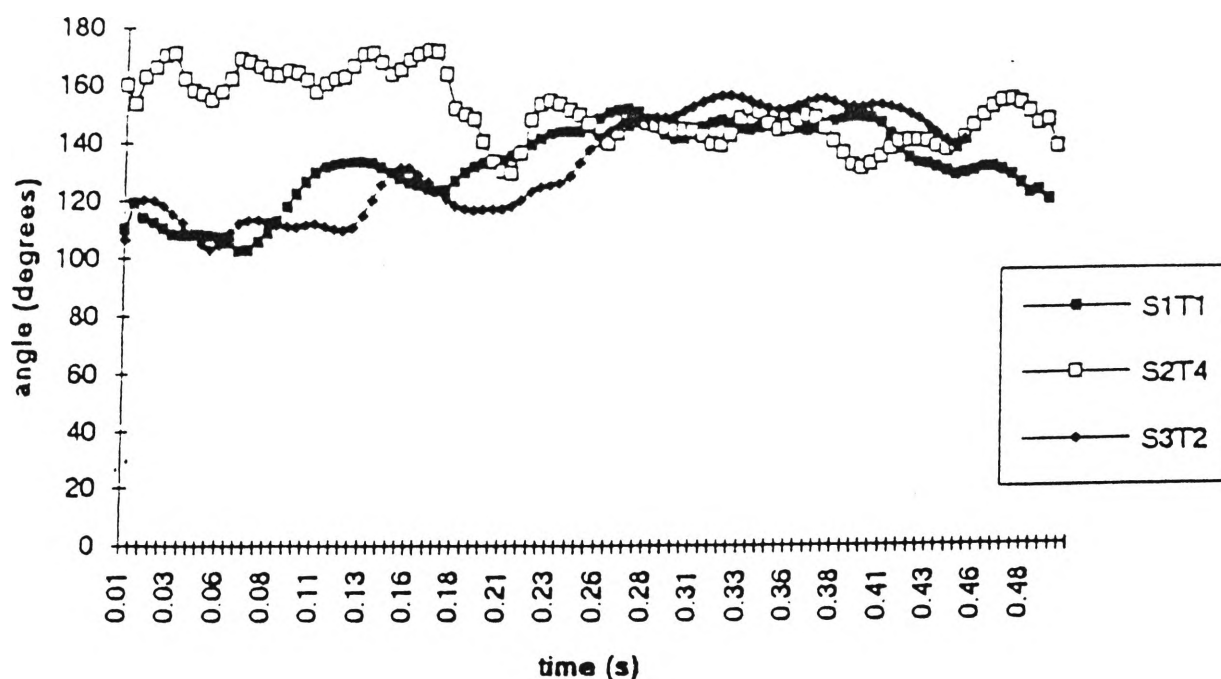


Figure 4.8: Comparison of knee and hip abduction/adduction between three trials.



(b) Knee abduction/adduction.

Apart from Subject 2 while negotiating the mogul, all subjects showed minimal identifiable difference in the abduction/adduction angles throughout the trials at the hip (Figure 4.8a). The actual values of the knee abduction/adduction angles were again not considered as important as the trends shown due to the accuracy limitations discussed earlier. A considerable difference in the knee abduction was shown in Figure 4.8b. Subjects 1 and 3 again showed very similar patterns but Subject 2 approached the reference mogul with less knee angulation. All subjects then showed similar angles of abduction across the mogul but there was an indication towards the end of the respective trials that S2T4 was again reverting to a less abducted knee while Subjects 1 and 3 were again abducting the knee.

Figure 4.8b indicated that Subject 2 both approached the turn and exited the turn with little knee angulation compared to Subjects 1 and 3 (180° = neutral position of no abduction or adduction). This suggested that Subjects 1 and 3 applied greater force to their edges through this angulation and therefore had a greater length of edge in contact with the snow at all times. This utilisation of the full length of the edges presumably permitted the elastic properties of the ski to accelerate the skier. Only at the time in which the vertex of the

mogul was being approached did Subject 2 show increased abduction at the knee and the ski was therefore used to little advantage to attain greater velocity.

This study therefore identified a possible variable, that is the abduction/adduction angle at the knee and hip joints, by which the 'carving' technique could be identified.

4.2.5 Active Leg Extension

In order to maintain control throughout a mogul run the skier should effectively absorb the forces experienced at impact with the mogul to prevent the ground reaction forces from forcing the skier to lose contact with the snow surface and thus becoming airborne for a sufficient period to land directly on the slope of the next mogul. The absorbing motion has been previously described as an active extension of the legs after passing the peak of the mogul (Ikegami *et al.*, 1987) thereby maintaining contact between the ski base and snow. Figure 4.9 illustrated the angles of flexion at the knee and hip joints throughout a trial that reflected the ability of the skier to absorb undulations introduced by the mogul.

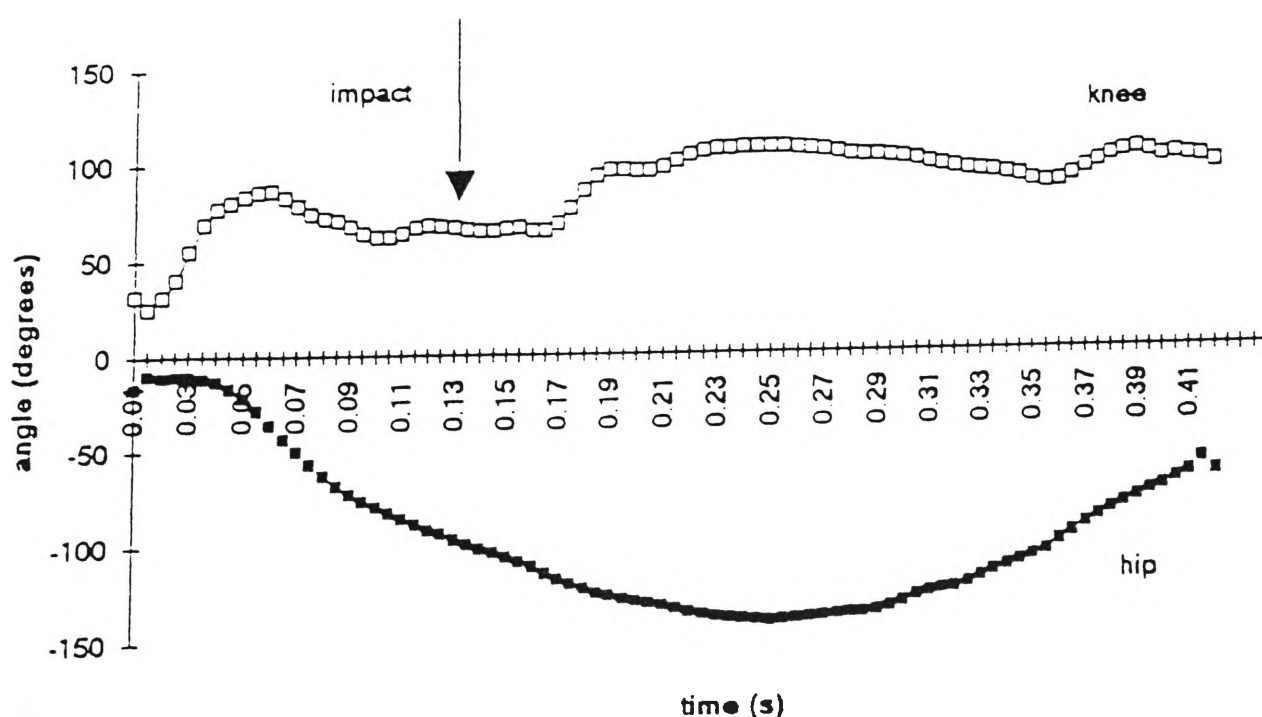


Figure 4.9: Knee and hip flexion/extension for S3T1.

Figure 4.9 showed that both the knee and hip joints, especially the latter, were extended (full extension = 0°) after the pre-reference mogul and then flexed as the reference mogul was approached. Impact appeared to have little effect on the angles of flexion/extension; in fact the knee was flexed to a greater degree (greater than 90°) 0.075 s prior to impact and did not flex to this angle again until 0.050 s after impact. The hip showed increased flexion throughout the complete phase of approaching the mogul and during impact with the mogul. The hip was rotated to a greater maximum angle of flexion (-130°) than the knee. However, whereas the knee remained at a consistent angle throughout the later part of the turn, the hip began extending again after the reference mogul had been passed. This hip extension was initiated prior to the vertex of the mogul having been passed, indicating the subject's intention to actively extend the leg down the far side of the mogul for benefit to both style (Australian Professional Ski Instructors, 1976) and force absorption (Ikegami *et al.*, 1987).

In Figure 4.9 the knee and hip were already being flexed more than 0.100 s prior to impact indicating that not only was there an active extension phase after the reference mogul had been passed but also an active flexion movement prior to impact. This was a mechanism whereby control could be maintained while negotiating the mogul by eliminating any passive movements induced by impact.

Presumably, if the subject was actively extending the legs after having passed the vertex of the mogul in order to reduce the force experienced when landing after the mogul, the angle of the torso long axis to the global z axis would have been approximately zero throughout the trial. Figure 4.10 showed the absolute angle of the torso long axis of S3T1 to the global z axis.

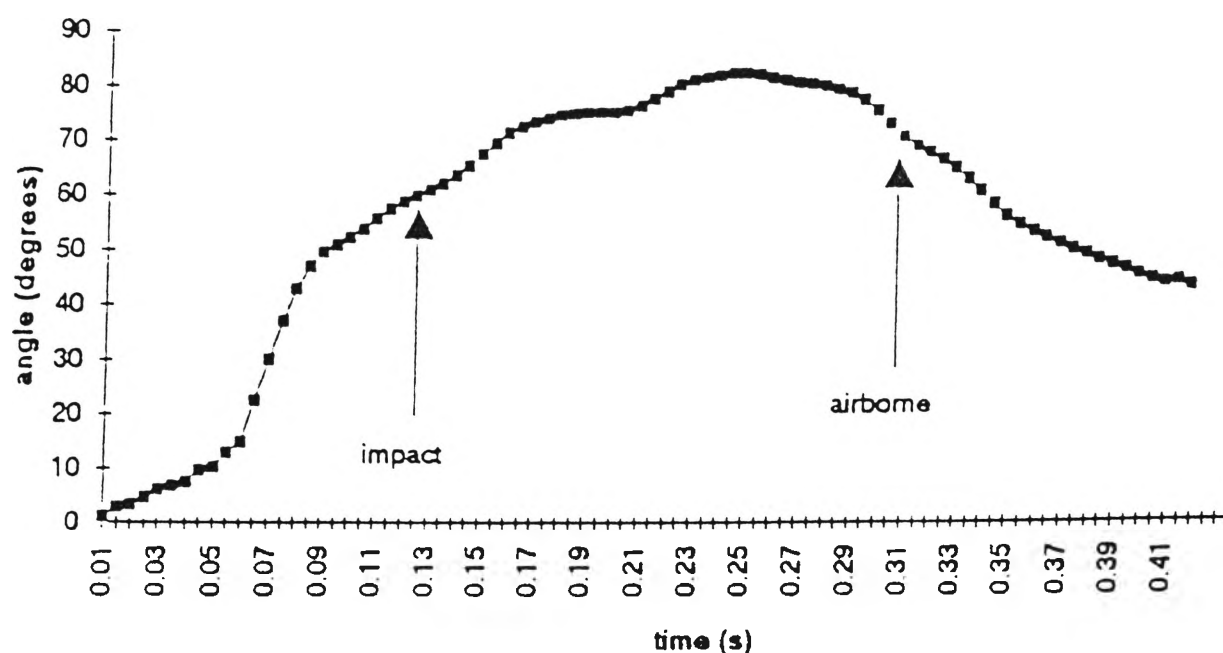


Figure 4.10: Angle of torso long axis relative to the global z axis for S3T1.

The global and local frames of reference used in this study had different orientations due to the requirements of the KinTrak software. The comparison of the local x axis of the torso to the global z axis in Figure 4.10 illustrated how, despite being defined in different orientations, these differing systems posed few problems in the calculation of related variables.

In Figure 4.10 the torso angle increased from almost fully aligned to the vertical global z axis (that is 0°) to a maximum angle of 80° and then this angle decreased relative to the global z axis after the vertex of the mogul had been passed. The torso long axis was therefore not vertically orientated throughout the negotiation of the mogul, but deviated from this position by approaching the horizontal (global x axis orientation) through hip flexion. This indicated that the increased angle of extension at the hip joint after the mogul had been negotiated was not purely a result of downward, active extension of the leg but also included movement of the torso to a more vertical orientation.

Ikegami *et al.* (1987) differentiated between skilled and beginner skiers by observing the extent of vertical motion of the head when skiing over a hump (see Section 2.1.4). In the present study, all subjects were elite mogul skiers and this precise differentiation was therefore not applicable. In the present study the subjects were questioned after each completed trial for a subjective indication of the success of the trial, that is how the trial 'felt'. Trends could be observed between poorly executed trials and successful trials. The stick figure representation of all trials (Appendix G) could be compared to those of the skilled skier presented in Ikegami *et al.* (1987). This indicated that the three elite skiers used in this study demonstrated a greater range of motion of the torso relative to the vertical axis and this was presumably a result of the skiers in this study negotiating the mogul at greater speeds than those in Ikegami *et al.* (1987). However the trajectories of the vertex of the skiers in this study compared to those of Ikegami *et al.* (1987) are similar, thus indicating stable posture of the torso relative to the lower limbs and therefore greater accelerations experienced at the knee joints than at the upper body.

4.2.6 Development of a Coaching 'Template'

The application for possible coaching purposes of the methodology used in this study could be described as the definition of 'templates' (or models) of specific variables for successful turns in mogul skiing. A successful turn could be defined as one chosen by qualified mogul skiing judges. In this study however, an indication of the success of each executed turn was provided by the subjects immediately after each trial was completed. The subjects were questioned on the quality of the turn executed in terms of the speed with which the mogul series had been negotiated, how 'in control' they had been and the rhythm felt throughout the trial. The most positive response for all trials was received from Subject 3 after trial 1. The analysis of the variables for this particular trial could therefore produce such a 'template'. This template or model could then be used as a direct comparison with the same variable analysed in other trials or as a base for coaching guidelines. As indicated in Figures 4.7 and 4.10 the angle of hip flexion/extension for S3T1 was smooth with minimal oscillations. General indications are therefore that minimal oscillation in hip flexion could be defined as such a variable to be used as a template.

- This template was then compared in Figure 4.11 with the same variable analysed for S2T3; one of the least successful trials as indicated by subjective feedback. Stick figure representations of subject motion for trials S3T1 and S2T3 were included in Figure 4.12 as

an overview of the motions occurring in these two trials. Stick figures of all trials are presented in Appendix G.

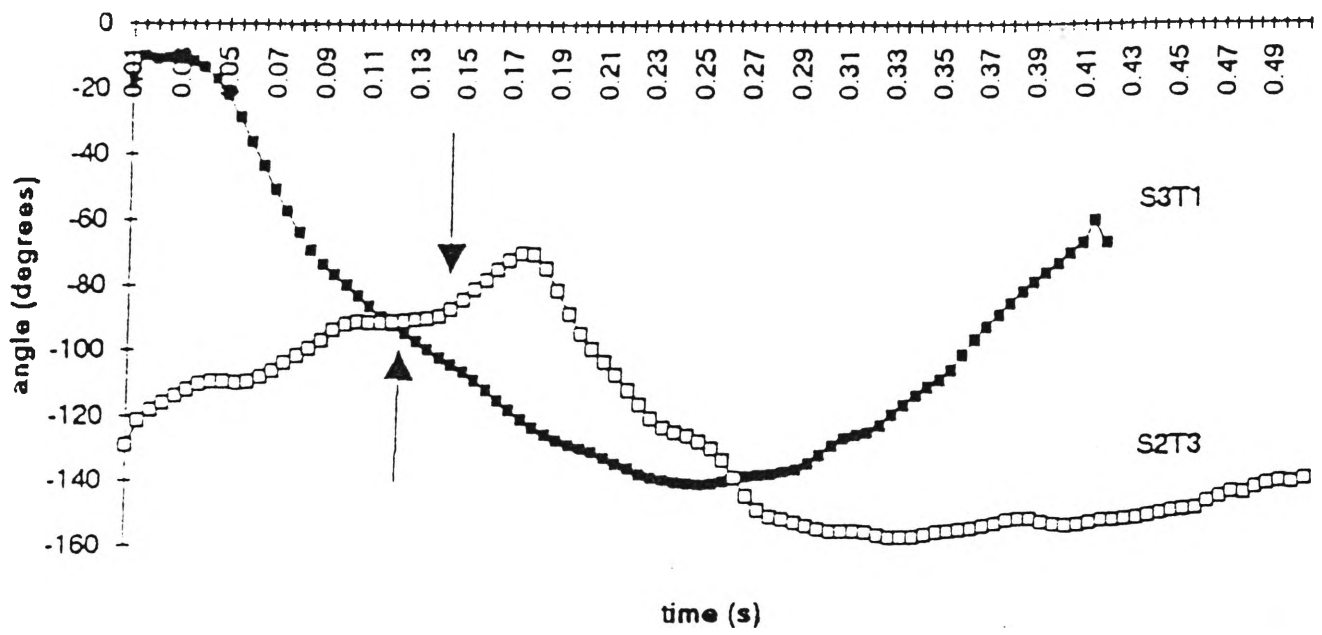
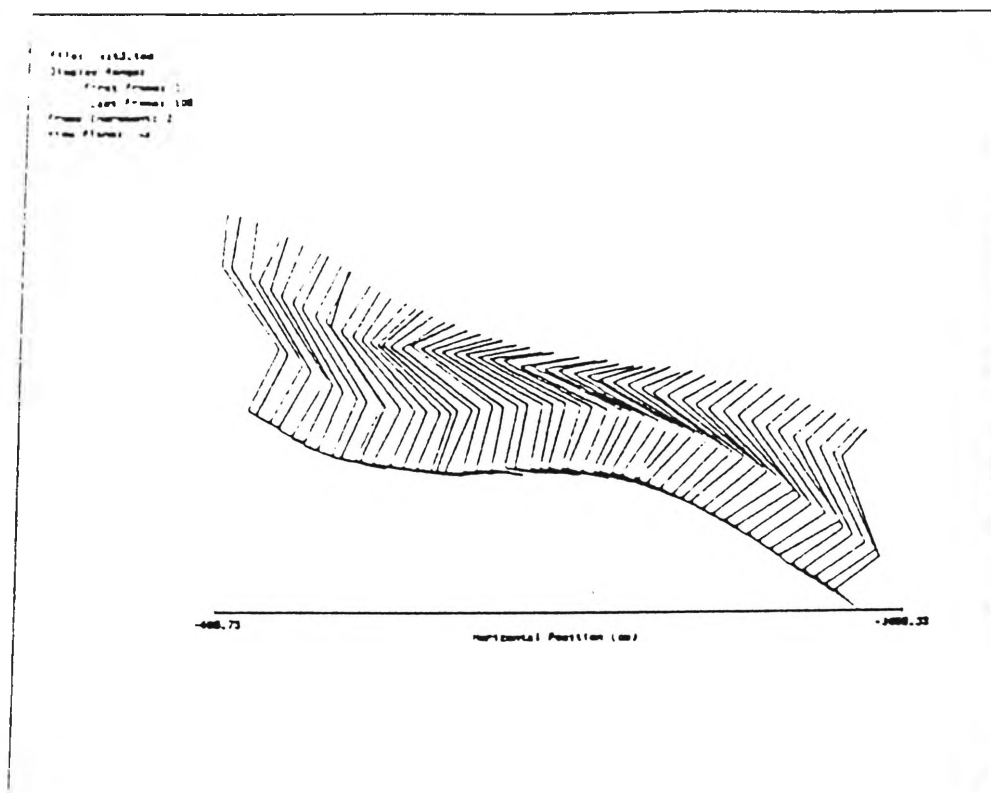
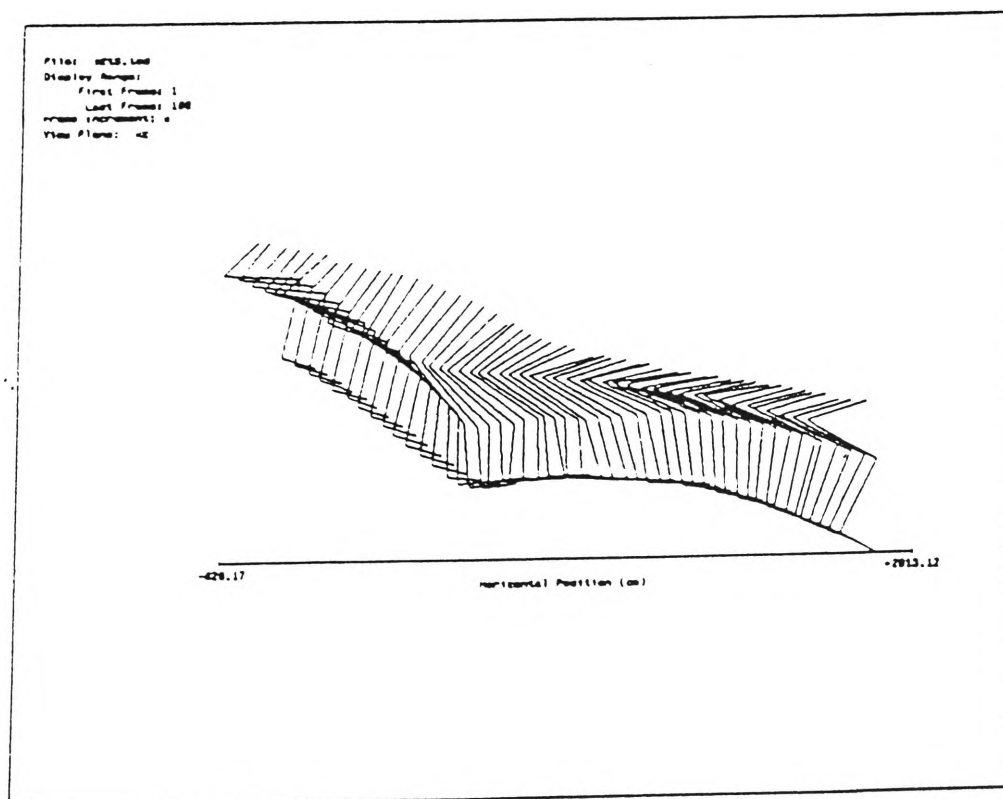


Figure 4.11: The development of a 'template' for a variable by using the pattern of hip flexion/extension through a turn.

The arrows in Figure 4.11 indicated the times at which impact occurred in the two trials represented.



(a) Stick figures S1T3.



(b) Stick figures S2T3.

Figure 4.12: Stick figure descriptions of trials S3T1 and S2T3

In this trial Subject 2 was in the air from the pre-reference mogul until the moment of impact at time 0.145 s. At the beginning of trial S2T3 the subject's hip was relatively flexed at -130° (torso and thigh aligned = -180°) and was extending until time 0.175 s (-70° , as compared to maximum extension of -10° for S3T1). At this point a rapid flexion at the hip was initiated. Immediately after impact (again after a phase lag of 0.025 s) S2T3 appeared to have been forced to passively flex at the hip as a result of the transmitted ground reaction force experienced when striking the mogul. This flexing motion then continued throughout the remainder of the trial. The different approach therefore appeared to have prevented Subject 2 from maintaining control while negotiating the reference mogul.

The template therefore has applications in determining the phase in which the subject had problems and subsequent recommendations concerning the improvement of this phase could be made.

The expertise and equipment necessary for the application of an analysis such as that employed in this study may not be readily available for use upon competitors in all competitions or at all levels. Therefore a previously obtained template of an elite subject can be used by coaches or competitors to give segment angles and sequences thereof at specific phases of a turn. Training methods could then be concentrated upon simulating these actions.

Stick figure representations of all trials produced in EV as presented in Figure 4.12 and in Appendix G are a representation of the trials viewed from the lateral, global xz plane. The segments were defined for the purposes of EV stick figures by proximal and distal joint markers connected by inelastic links.

4.3 Possible Injury Mechanisms

4.3.1 Anterior Cruciate Ligaments of the Knee

Read and Herzog (1992) described an injury mechanism occurring as a result of an anterior push on the tibia by the ski boot combined with a strong quadriceps muscle contraction (see Section 2.4.1). Both Figures 4.1 (ankle) and 4.2 (knee) illustrated postural phases in the mogul skiing motions of SIT1 indicative of the descriptions given by Read and Herzog (1992). These indicated both a slight knee extension and what Read and Herzog (1992) described as a posteriorly directed ankle (plantarflexion). Furthermore both these phases were immediately after impact, indicating that negotiation of a mogul field possibly caused the subjects to adopt positions that would place them at risk of injury. These results confirmed a situation described in the literature and were supplemented by the momentary hip extension (also at impact) shown in Figure 4.7. Although this hip extension was shown in different trials with respect to the mechanisms occurring at the ankle and the knee, it was a further possibility of a mechanism by which a mogul skier may load the ACL.

Figure 4.9 showed a greater range of motion of flexion/extension occurring at the hip than at the knee. This was a result of both greater extension at the beginning of the trial and greater flexion while negotiating the mogul. At this latter stage the subject brought the thighs and chest almost together (hip angle of approximately -135°) while the knees remain relatively extended (very little flexion past 100°). This could have represented a mechanism to prevent the situation described by Read and Herzog (1992) in which the body's centre of gravity was positioned so far posteriorly relative to the direction of the motion that the skier had difficulty in producing the quadriceps muscle force necessary to pull the thighs and torso back to upright posture.

4.3.2 Medial Collateral Ligaments of the Knee

The limitation of this study concerning the accuracy of the angles of internal/external rotation at the knee has been outlined in Section 4.2.2. This section was therefore based upon the patterns shown in the motions of the skiers in the realisation that it would have been a fallacy to accept the values at face value.

The most frequently described mechanism of injury to the MCL of the knee in alpine skiing was a combined external rotation of the tibia with flexion of the knee (Burns *et al.*, 1991). The results of this study provided an indication that in mogul skiing the knee was generally internally rotated and any rotation of the knee towards a neutral or externally rotated knee was generally accompanied by extension. This was demonstrated in Figure 4.3. It was interesting to note the motion occurring immediately after impact where the data indicated that the knee may have become externally rotated in conjunction with an extension from 40° to 8°. This indicated that impact transmitted forces to the joint causing either passive motion or motion in opposition to deliberate muscle activity stabilising the knee joint. One such passive motion was external rotation at the knee. However Figure 4.3 indicated a possibility that the subject responded with a protective extension thus avoiding injury potential. Notice again that the joint angular response to the impact appeared to be delayed by approximately 0.025 second. As impact was measured as the moment of ski boot impact with the mogul this delay could not be attributed to flexion of the ski but was more likely the result of the elastic properties of the ski boot and the force attenuating properties of the ankle joint.

This study indicated a number of trials in which external rotation at the knee independent of motions at the hip may have been present at the impact stage (for example see SIT3, Figure 4.3). However any such movement shown in this study was accompanied by an extension at the knee, thus indicating a possible mechanism by which the knee protects the MCL when vulnerable during external rotation. Furthermore trial SIT3 appeared to have been an exception and the majority of trials executed in this study showed no stage at which the knee approached an angle of external rotation at the knee at impact (as shown by Figures 4.4 and 4.5). In these trials impact produced only a minor deviation in internal rotation during relatively steady flexion of the knee and these deviations could not be seen as significant as the accuracy of the calculation of these angles permitted no differentiation

between such minor fluctuations.. This injury mechanism was therefore not identified in elite mogul skiers in this study

The subjects in this study presumably prevented external rotation at the knee during flexion by contracting the hamstring muscle group at this stage to provide stability at the knee against internal/external rotations. It was presumably at instances when this protective mechanism failed to operate that injuries could occur and this was likely to occur when the skier was fatigued and out of control, for example towards the end of a competitive mogul run. At this stage the muscles stabilising the knee were possibly not as capable of providing sufficient support to counteract moments transmitted to the knee through the long lever arm of the ski. A competitive mogul run is both of longer duration and contains larger moguls than in this study and the competitors were therefore more likely to be fatigued and skiing with less control than exhibited in the trials of this study. The ski tips may strike a large, solid mogul in a direction not parallel to the skier's direction of travel with the skier travelling at up to 20 m/s. A scenario is then established in which the knee was externally rotated at ski tip impact and the skier may not have enough control to stabilise the flexed knee and prevent potential ligament damage.

Definitions of the two major competitive mogul skiing techniques of 'wriggling' and 'carving' indicated that the latter included a greater application of the skis' edges throughout the turns. The 'wriggling' technique utilised only approximately the centre 1/3 of the length of the ski's edge (Blundell, 1992) and therefore has a greater proportion of the ski not being actively used to control the turn. This inactive portion of the ski was more likely to strike a mogul at awkward angles and transmit moments to the knee which the skier is unable to control. The 'carving' technique permits the skier to have greater control over the motions of the skis by holding edge contact with the snow surface and angulating the knee to actively force the legs through the turns.

4.3.3 Recommendations for Injury Prevention

As mentioned previously knee flexion in the trials in this study was accompanied by internal rotation and therefore appeared to be a relatively safe posture. However this may lead to further injury potential caused by hyperextension at the knee. A number of trials indicated flexion/extension angles at the knee approaching 0° (full extension) and S1T1 (Figure 4.2) showed the knee extending past 0° only 0.100 second prior to impact. This

leads to the possibility of an anterior dislocation of the knee (and therefore ACL damage) if the skier failed to begin a flexion movement prior to impact. This mechanism could be prevented by a hamstring contraction causing the flexion at the knee and also assisting the ACL in knee stabilisation. An unfatigued competitor, skiing in control may be able to prevent knee hyperextension and provide adequate time for knee flexion prior to impact with the mogul. This example showed the major method by which injuries could be prevented in mogul skiing in that a skier under control was less likely to be forced into postures that could cause injury.

In competitive mogul skiing the skiers are trying to ski at the highest possible velocity through moguls up to 1.5 m high while executing difficult manoeuvres. The recommendation to ski 'under control', while true was therefore inappropriate as the nature of the sport necessarily renders some competitors 'out of control' if they were skiing to their maximum ability.

The potential injury mechanisms described in this study indicated that a mechanism by which at least the reduction, if not the total prevention, of all of these would be possible was the active contraction of certain muscle groups throughout specific stages of the turn. These recommendations would prove difficult for novice skiers encountering a mogul field to observe and were intended for expert mogul skiers for whom the motions, despite their high velocity, are so developed that technique could be modified by practising the contractions of certain muscle groups during training. Recommendations to reduce the risk of injury include:

- 1) A contraction of the hip flexors in the approach to the mogul was recommended to achieve greater hip flexion and therefore preventing the upper body centre of gravity from being located posteriorly relative to the direction of travel that the quadriceps contraction necessary to pull it forward again would endanger the ACL.
- 2) A contraction of the hamstring muscles when the knees were flexed was recommended to prevent any external rotation of the tibia relative to the femur in this position.
- 3) A hamstring co-contraction with the quadriceps was also recommended when the leg is extended to prevent hyperextension at the knee and therefore anterior dislocation of the tibia relative to the femur.

- 4) Following indications drawn from ski injury literature it was also recommended that muscles of the lower limbs are contracted in any situation in which the skier realises that control is lost and a fall is inevitable. This stabilises the knee joint against any damage resulting from multi-directional forces transmitted through the ski and leg if the bindings do not release.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

The alpine skiing freestyle sport of mogul skiing is receiving increasing attention and more competitors both in Australia and world wide as a result of its inclusion as a full medal event in the Winter Olympic Games, 1992. Personal correspondence with a number of elite competitors has led to an indication of a large proportion of competitors in this sport suffering from knee injuries, particularly of the ligaments. A demand for a detailed analysis of mogul skiing has therefore arisen to help in technique modification and injury prevention.

In this study three elite competitive mogul skiers were filmed at 200 frames per second by two LOCAM high speed cameras whilst executing a turn on a reference mogul. Each subject was filmed for four trials. The space in which the motion of interest occurred was calibrated for three-dimensional analysis by filming a 2 m aluminium cube with 32 markers of known spatial positions prior to each trial. The processed film was manually digitised by projection with a Vanguard projection unit onto a Graph Pen 8 sonic digitising screen. The markers on the cube were digitised in three random frames for each trial and the average of these three frames taken as the mean marker position. Three non-colinear markers are necessary per segment in order to determine its position in three-dimensional space. The segments to be used for analysis were the left foot, leg and thigh, the right leg and thigh and the torso. Nineteen markers (one point on the head was also included) on each subject were digitised in consecutive frames from a frame prior to maximal knee extension before the reference mogul to the last frame in which all markers were in the cameras' fields of view. The two-dimensional u and v coordinates of all markers from the two cameras were then combined with the calibration cube data as input into computer software developed to determine the three-dimensional x, y, and z coordinates of all the markers using the Direct Linear Transformation (DLT) technique.⁷ The resulting x, y, z files were then the input for the Motion Analysis Corporation (MAC) KinTrak software running on a Sun UNIX workstation. The three-dimensional coordinates combined with

manual transformation measurements of the distance of each marker to the origin of its local coordinate system allowed the calculation of the position of the anatomical frames of reference for each segment. The rotations of flexion/extension, abduction/adduction and internal/external rotation at the ankle, knee and hip joints could then be determined as angles of rotation about Joint Coordinate System (JCS) angles defined by KinTrak. A graphical analysis of these variables and linear velocities and accelerations of certain marker positions was then conducted producing approximately 150 graphs. A selection of the most representative examples illustrating the various variables and also any trials demonstrating exceptional variable patterns was then made for presentation in this study.

Angular data produced for rotations at the joints concerned were used as kinematic descriptors of the mogul skiing turns executed.

Any rotations occurring at the ankle were shown to be predominantly about the dorsiflexion/plantarflexion axis with a range of motion in this rotation of 35° . The variables of flexion/extension at the knee and hip proved particularly useful as indications of good technique in terms of negotiating the reference mogul with minimum vertical deviation of the upper body as a result of transmitted ground reaction forces. Active flexion at the knee and hip prior to impact and also active extension after the peak of the mogul had been passed were both identified and these correlated with guidelines in the literature for better style and also more efficient force absorption. The variable of abduction/adduction at the knee was used to identify the 'carving' technique as opposed to the 'wriggling' technique. The three-dimensional analysis showed many variables useful for coaching purposes of competitive mogul skiers. The pattern of hip flexion/extension was used as an example of such a variable that could be described as a 'template' for comparison between two subjects.

A comparison was made of the variables analysed in mogul skiing with positions described in the literature as potentially causing injury. An injury mechanism of the ACL has been described in the literature as an anterior push on the tibia by the ski boot combined with a strong quadriceps contraction. A posture was identified in this study to occur in mogul skiing that may represent this injury mechanism. Another posture that may place excessive strain on the ACL was also identified when the knee became hyperextended immediately prior to impact with the mogul. There was no indication in this study that mogul skiing produced the most commonly described skiing injury mechanism, that of external rotation at the knee being combined with flexion.

5.2 Conclusions

- 1) The combination of high speed cinematography with the three-dimensional Direct Linear Transformation technique proved successful in collecting data of a dynamic movement in difficult alpine conditions and provided accurate three-dimensional coordinates of the required points.
- 2) All three subjects exhibited flexion at the knee prior to impact and to some extent active extension of the thigh and leg after the peak of the mogul had been passed in accordance with instruction guidelines for decreasing ground reaction forces both at impact and when landing after the mogul.
- 3) A 'template' was described to aid in competitive mogul skier coaching. This was by using graphical analyses of variables important for a mogul skiing run. Such a variable obtained from a successful turn could be compared with the same variable obtained off any mogul skiing turn and any differences in critical phases of the turn identified and subsequently rectified by coaching techniques.
- 4) Flexion at the hip appears to be a protective mechanism employed to prevent the body's centre of gravity from lying too far posteriorly; a position that has been described previously as a possible injury mechanism at the knee.
- 5) A combination of external rotation and flexion at the knee which is the most commonly described injury mechanism in mogul skiing appeared to be avoided in the present study by any external knee rotation demonstrated by the subjects being accompanied by extension.

- 6) Mogul skiers are recommended to actively contract the hip flexors prior to impact with the mogul to avoid the upper body centre of gravity from being forced posteriorly relative to the direction of the motion. This is to avoid a posture that has been linked to injury of the ACL of the knee.
- 7) Mogul skiers are recommended to avoid full knee extension in the approach to a mogul, thus avoiding potential injury to the ACL.

CHAPTER 6

RECOMMENDATIONS FOR FURTHER STUDY

- 1) The coaching and judging potential of the 'templates' described in this study needs further exploration. A method by which mogul skiers could wear suits containing reflective markers identifiable during competition skiing with automatic, simultaneous tracking and digitising of these could provide a computer based, objective judging criterion in mogul skiing competition by comparison to theoretical 'perfect templates'.
- 2) A fundamental problem found throughout this study was the multitude of conventions used for the definition of the x, y and z axes' orientations in unit coordinate systems. In order to standardise further studies one universal convention should be adopted in biomechanics; the logical choice appears to be the force plate convention of z (vertical), y (anterior/posterior) and x (medial/lateral). If this posed problems specific to any studies (such as the visibility of the calibration cube origin did in this study) efforts should be made to subsequently transform any data obtained to these conventions.
- 3) There is a need for further kinematic studies to concentrate specifically on the different techniques involved in competitive mogul skiing and identify optimum techniques in terms of safety and effectiveness in fulfilling and possibly determining judging criteria.
- 4) The injury potential inherent to the sport of mogul skiing requires kinematic data for the identification of injury mechanisms. Future studies should combine these data with quantification of ground reaction forces for the calculation, through inverse dynamics, of the forces experienced at the joints of the lower limb.
- 5) The range of motion of the leg in various rotations occurring in mogul skiing, together with the directions of forces applied through the ski boot to the ski bindings makes mogul skiing an extreme test of binding function and design, and future study could therefore be directed specifically at the function (or non-function) of binding release mechanisms whilst skiing moguls.

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APPENDIX A

THE DIRECT LINEAR TRANSFORMATION

1. Calculation of 11 DLT Parameters

The DLT equations 5 and 6 (page 39) relate the x and y (U and V) film coordinates of a known point to the three-dimensional x , y , and z coordinates of that point through the calculation of 11 DLT parameters. The minimum of six control points with precisely known position will yield 12 such equations for the calculation of 11 constants per camera. Equations 5 and 6 can be rewritten in matrix form as :

X1	Y1	Z1	1	$-U1 \times X1$	$-U1 \times Y1$	$-U1 \times Z1$	0	0	0	0		U1
X2	Y2	Z2	1	$-U2 \times X2$	$-U2 \times Y2$	$-U2 \times Z2$	0	0	0	0		U2
X3	Y3	Z3	1	$-U3 \times X3$	$-U3 \times Y3$	$-U3 \times Z3$	0	0	0	0	L1	U3
X4	Y4	Z4	1	$-U4 \times X4$	$-U4 \times Y4$	$-U4 \times Z4$	0	0	0	0	L2	U4
-	-	-	-	-	-	-	-	-	-	-	L3	-
-	-	-	-	-	-	-	-	-	-	-	L4	-
-	-	-	-	-	-	-	-	-	-	-	L5	-
Xn	Yn	Zn	1	$-Un \times Xn$	$-Un \times Yn$	$-Un \times Zn$	0	0	0	0	L6	Un
0	0	0	0	$-V1 \times X1$	$-V1 \times Y1$	$-V1 \times Z1$	X1	Y1	Z1	1	L7	V1
0	0	0	0	$-V2 \times X2$	$-V2 \times Y2$	$-V2 \times Z2$	X2	Y2	Z2	1	L8	V2
0	0	0	0	$-V3 \times X3$	$-V3 \times Y3$	$-V3 \times Z3$	X3	Y3	Z3	1	L9	V3
0	0	0	0	$-V4 \times X4$	$-V4 \times Y4$	$-V4 \times Z4$	X4	Y4	Z4	1	L10	V4
-	-	-	-	-	-	-	-	-	-	-	L11	-
-	-	-	-	-	-	-	-	-	-	-		-
-	-	-	-	-	-	-	-	-	-	-		-
0	0	0	0	$-Vn \times Xn$	$-Vn \times Yn$	$-Vn \times Zn$	Xn	Yn	Zn	1		Vn

(16)

Where : n is the number of control points used.

Writing Equation 16 in matrix and vector notation gives :

$$\mathbf{A} \cdot \bar{\mathbf{x}} = \bar{\mathbf{b}} \quad (17)$$

Where :

\mathbf{A} is an 11 by $2n$ matrix,

$\bar{\mathbf{x}}$ is a vector of 11 elements representing the DLT parameters, and

$\bar{\mathbf{b}}$ is a vector of $2n$ elements representing the film coordinates of the control points in one camera.

Premultiplying both sides of (17) by the transpose of \mathbf{A} gives :

$$\mathbf{A}^T \mathbf{A} \cdot \bar{\mathbf{x}} = \mathbf{A}^T \cdot \bar{\mathbf{b}} \quad (18)$$

Where :

$\mathbf{A}^T \mathbf{A}$ is a square 11 by 11 matrix derived from the multiplication of \mathbf{A} (11 by $2n$) and \mathbf{A}^T ($2n$ by 11), and

$\mathbf{A}^T \cdot \bar{\mathbf{b}}$ is a vector of 11 elements.

A set of 11 linear equations with 11 variables has therefore been created which can be solved by Gaussian elimination and back substitution. This is a least squares solution for the vector $\bar{\mathbf{x}}$ (the 11 DLT parameters). For proof of the least squares algorithm see Atkinson (1988).

2. Calculation of Object Coordinates

From the two DLT equations; 5 and 6 one can get :

$$- \quad L5XU + L6YU + L7ZU + U = L1X + L2Y + L3Z + L4 \quad (19)$$

$$L5XV + L6YV + L7ZV + V = L8X + L9Y + L10Z + L11 \quad (20)$$

and consequently in terms of the unknown spatial coordinates :

$$(L1 - L5U)X + (L2 - L6U)Y + (L3 - L7U)Z = U - L4 \quad (21)$$

$$(L8 - L5V)X + (L9 - L6V)Y + (L10 - L7V)Z = V - L11 \quad (22)$$

Equations 21 and 22 written in matrix form to accomodate for n cameras are :

$$\begin{array}{ccccccc} (L1 - L5 \times U)_1 & (L2 - L6 \times U)_1 & (L3 - L7 \times U)_1 & & (U1 - L4)_1 & & \\ (L1 - L5 \times U)_2 & (L2 - L6 \times U)_2 & (L3 - L7 \times U)_2 & & (U1 - L4)_2 & & \\ - & - & - & & - & & \\ (L1 - L5 \times U)_n & (L2 - L6 \times U)_n & (L3 - L7 \times U)_n & \times \begin{array}{c} X \\ Y \\ Z \end{array} & = & (U1 - L4)_n & \\ (L8 - L5 \times V)_1 & (L9 - L6 \times V)_1 & (L10 - L7 \times V)_1 & & (V1 - L11)_1 & & \\ (L8 - L5 \times V)_2 & (L9 - L6 \times V)_2 & (L10 - L7 \times V)_2 & & (V1 - L11)_2 & & \\ - & - & - & & - & & \\ (L8 - L5 \times V)_n & (L9 - L6 \times V)_n & (L10 - L7 \times V)_n & & (V1 - L11)_n & & \end{array} \quad (23)$$

This is in the same form as Equation 16 and by again premultiplying both sides by the transpose of the first matrix a least squares solution can be obtained for the three spatial coordinates, X , Y , and Z .

APPENDIX B

SAMPLE OUTPUT OF DLT PROGRAMME

FOR TRIAL S3T2

1. DLT Coefficients

```

Dlt Co-efficients for file sub2c1a
1 :      -1.25513324
2 :      -0.13455173
3 :      -0.01617246
4 :      3917.77299060
5 :      -0.00000600
6 :      -0.00008172
7 :       0.00000696
8 :      -0.02674242
9 :      -0.07900790
10 :       1.25728768
11 :      3789.80910010
Dlt Co-efficients for file sub2c2b
1 :      -1.00353904
2 :       0.39740315
3 :       0.17227655
4 :      3211.48497531
5 :      -0.00006209
6 :      -0.00007943
7 :       0.00003293
8 :       0.07874804
9 :      -0.02491496
10 :       1.08247307
11 :      2886.49870379

```

2. Two-Dimensional Marker Predictions for both Camera Views (Digitising Units)

```

Marker Predictions from DLT Co-efficients for file :sub2c1a
Marker:1 Label: 1X
X : 3920.0000 3917.7729 -2.227
Y : 3800.6667 3789.8091 -10.858
Marker:2 Label : 2X does not exist in this UV file
Marker:3 Label: 3X
X : 4488.6665 4479.6494 -9.017
Y : 4334.6666 4335.3613 1.195
Marker:4 Label: 4X
X : 4364.6665 4365.4814 0.815
Y : 4358.0000 4346.2759 -11.724
Marker:5 Label: 5X
X : 4405.0000 4405.6646 0.665
Y : 3788.0000 3781.6172 -6.383
Marker:6 Label : 6X does not exist in this UV file

```

```

Marker:7 Label: 7X
X : 1434.0000 1421.5089 -12.491
Y : 1296.3334 1232.3890 -63.444
Marker:8 Label: 8X
X : 1346.3334 1337.3450 11.212
Y : 1356.6665 1340.9429 -15.724
Marker:9 Label: 9X
X : 4054.3333 4050.3682 -3.965
Y : 3953.3333 3954.6145 1.281
Marker:10 Label: 10X
X : 4193.0000 4197.3990 4.399
Y : 4133.0000 4138.1084 5.108
Marker:11 Label: 11X
X : 3358.6667 3366.0955 7.429
Y : 4341.3335 4345.7236 4.390
Marker:12 Label: 12X
X : 2371.0000 2374.9153 3.915
Y : 4332.0000 4245.1758 -86.822
Marker:13 Label: 13X
X : 1374.3334 1375.5372 1.204
Y : 4129.0000 4132.6846 3.685
Marker:14 Label: 14X
X : 1394.0000 1391.5546 -2.445
Y : 3947.0000 3946.5071 -0.493
Marker:15 Label: 15X
X : 2259.3333 2250.2515 -9.082
Y : 3773.3333 3784.3713 11.038
Marker:16 Label: 16X
X : 3090.3333 3078.0706 -12.263
Y : 3778.0000 3787.0708 9.071
Marker:17 Label: 17X
X : 3952.6667 3946.9138 -5.753
Y : 2967.3333 2963.7107 -3.623
Marker:18 Label: 18X
X : 3969.3333 3976.3723 7.039
Y : 2134.6667 2128.6096 -6.057
Marker:19 Label: 19X
X : 4397.6665 4403.1270 5.461
Y : 3349.0000 3353.5962 4.596
Marker:20 Label: 20X
X : 4439.0000 4441.1440 2.144
Y : 2351.6667 2351.1843 -0.482
Marker:21 Label: 21X
X : 1375.6666 1378.5686 2.902
Y : 3342.6667 3336.7976 -5.869
Marker:22 Label: 22X
X : 1406.6666 1399.3291 -6.738
Y : 2319.6667 2313.5134 -6.153
Marker:23 Label: 23X
X : 1422.3334 1423.4791 1.146
Y : 2935.0000 2936.5229 1.523
Marker:24 Label: 24X
X : 1437.3334 1441.3040 3.971
Y : 2090.3333 2090.9395 0.606
Marker:25 Label: 25X does not exist in this UV file
Marker:26 Label: 26X does not exist in this UV file
Marker:27 Label: 27X
X : 3472.3333 3472.7537 0.420
Y : 1312.6666 1320.5056 7.839
Marker:28 Label: 28X

```

X : 2461.6667 2430.0225 -4.644
 Y : 1206.0000 1298.3121 2.312
 Marker:19 Label : VX does not exist in this CV file
 Marker:20 Label : VX does not exist in this CV file
 Marker:21 Label: WX
 X : 2308.0000 2319.5645 11.564
 Y : 1216.6666 1250.6102 3.047
 Marker:22 Label: XX
 X : 3132.6667 3160.2273 7.351
 Y : 1262.6666 1261.1019 -2.365
 Marker Predictions from DLT Co-efficients for file :rub2c2b
 Marker:1 Label: 1X
 X : 3214.0000 3211.4849 -2.515
 Y : 2894.3333 2886.4988 -7.834
 Marker:2 Label : 2X does not exist in this CV file
 Marker:3 Label: 3X
 X : 4733.0000 4737.3330 4.333
 Y : 849.6667 846.3521 -2.315
 Marker:4 Label: 4X
 X : 4774.6665 4776.3374 2.171
 Y : 3282.3333 3276.7869 -5.546
 Marker:5 Label: 5X
 X : 1360.3334 1359.3982 -0.935
 Y : 3478.3333 3480.6692 2.336
 Marker:6 Label: 6X
 X : 1033.6666 1038.4738 4.807
 Y : 1080.3334 1071.7291 -8.604
 Marker:7 Label: 7X
 X : 2543.3333 2528.4187 -14.915
 Y : 1257.0000 1247.9470 -9.053
 Marker:8 Label: 8X
 X : 2774.3333 2782.2949 7.962
 Y : 4197.0000 4188.9575 -8.042
 Marker:9 Label: AX
 X : 3678.3333 3676.8806 -1.453
 Y : 3032.0000 3032.2666 -0.732
 Marker:10 Label: BX
 X : 4193.6665 4193.2695 -0.397
 Y : 3194.3333 3194.0059 -0.327
 Marker:11 Label: CX
 X : 4181.6665 4177.0404 -4.626
 Y : 3617.6667 3621.1262 3.459
 Marker:12 Label: DX
 X : 3524.3333 3524.9932 0.660
 Y : 3889.6667 3887.5171 -2.150
 Marker:13 Label: EX
 X : 2236.3333 2243.6841 7.351
 Y : 3915.0000 3920.8484 5.848
 Marker:14 Label: FX
 X : 1768.6666 1770.8463 2.180
 Y : 3680.0000 3685.4795 5.479
 Marker:15 Label: GX
 X : 2032.3334 2033.2610 0.928
 Y : 3255.6667 3264.4863 8.820
 Marker:16 Label: HX
 X : 2650.6667 2641.4346 -9.232
 Y : 3066.0000 3069.3774 3.377
 Marker:17 Label: IX
 X : 3169.0000 3166.0491 -2.951
 Y : 2215.0000 2212.0664 -2.934

```

Marker:18 Label: JX
X : 3118.0000 3118.4492 0.449
Y : 1504.0000 1505.5166 1.517
Marker:19 Label: KX
X : 4763.3335 4764.3332 1.000
Y : 2578.3333 2578.6836 0.350
Marker:20 Label: LX
X : 4745.3335 4751.5640 6.229
Y : 1737.0000 1737.4762 0.476
Marker:21 Label: MX
X : 2704.3333 2704.0671 -0.266
Y : 3275.6667 3272.8533 -2.813
Marker:22 Label: NX
X : 2627.6667 2620.2930 -7.374
Y : 2293.6667 2291.7947 -1.872
Marker:23 Label: OX
X : 1256.3334 1258.4545 2.121
Y : 2716.3333 2714.4719 -1.861
Marker:24 Label: PX
X : 1151.0000 1153.0773 2.077
Y : 1916.0000 1914.6230 -1.377
Marker:25 Label : QX does not exist in this UV file
Marker:26 Label : RX does not exist in this UV file
Marker:27 Label: SX
X : 4086.6667 4088.5286 1.862
Y : 950.6667 967.0630 16.396
Marker:28 Label: TX
X : 3361.0000 3358.3091 -2.691
Y : 1088.6666 1096.1245 7.458
Marker:29 Label: UX
X : 1967.3334 1962.1334 -5.200
Y : 1181.6666 1177.6967 -3.970
Marker:30 Label: VX
X : 1473.0000 1470.3630 -2.637
Y : 1124.0000 1125.9230 1.923
Marker:31 Label: WX
X : 1779.0000 1787.0795 8.079
Y : 954.0000 955.9040 1.904
Marker:32 Label : YX does not exist in this UV file

```

3. Resultant Distances of Predicted Calibration Point Positions to Measured Positions (mm)

```

Marker:1 Label: 1X
X : 0.0000 -2.1079 -2.108
Y : 0.0000 0.3429 0.343
Z : 0.0000 3.6213 3.621
Total Error : 8.881885
Marker:2 Label : 2X visible in less than 2 cameras.
Marker:3 Label: 3X
X : 0.0000 -7.9982 -7.998
Y : 2015.0000 2003.0379 -11.962
Z : -2015.0000 -2013.8924 1.108
Total Error : 14.432229

```

Marker:4 Label: 4X

X : 0.0000 -0.7975 -0.797
Y : 2015.0000 2011.5034 -3.497
Z : 0.0000 7.6814 7.681

Total Error : 8.477359

Marker:5 Label: 5X

X : 2015.0000 2014.3528 -0.647
Y : 0.0000 -1.3777 -1.378
Z : 0.0000 2.7733 2.773

Total Error : 3.163525

Marker:6 Label: 6X visible in less than 2 cameras.

Marker:7 Label: 7X

X : 2015.0000 2007.1685 -7.331
Y : 2010.0000 2014.9108 4.311
Z : -2019.0000 -2015.1737 3.326

Total Error : 10.004451

Marker:8 Label: 8X

X : 2015.0000 2021.4816 6.482
Y : 2013.0000 2010.8938 -2.106
Z : 0.0000 7.3423 7.342

Total Error : 10.017799

Marker:9 Label: 9X

X : 0.0000 -2.3411 -2.341
Y : 675.0000 674.0503 -0.950
Z : 0.0000 0.1557 0.156

Total Error : 2.999649

Marker:10 Label: 10X

X : 0.0000 5.1626 5.163
Y : 1344.0000 1350.1686 6.169
Z : 0.0000 -4.0789 -4.079

Total Error : 9.018965

Marker:11 Label: 11X

X : 676.0000 681.9976 5.998
Y : 2015.0000 2025.2371 10.237
Z : 0.0000 -6.1278 -6.128

Total Error : 13.353586

Marker:12 Label: 12X

X : 1340.0000 1344.4055 4.406
Y : 2015.0000 2020.9026 5.903
Z : 0.0000 -6.5525 -6.553

Total Error : 9.858221

Marker:13 Label: 13X

X : 2015.0000 2015.8777 0.878
Y : 1344.0000 1335.6964 -8.304
Z : 0.0000 -1.9393 -1.939

Total Error : 3.572115

Marker:14 Label: 14X

X : 2015.0000 2012.6703 -2.330
Y : 669.0000 661.1081 -7.892
Z : 0.0000 0.5598 0.560

Total Error : 8.247567

Marker:15 Label: 15X

X : 1343.0000 1335.9494 -7.051
Y : 0.0000 -11.0747 -11.075
Z : 0.0000 -5.6205 -5.620

Total Error : 14.281107

Marker:16 Label: 16X

X : 679.0000 670.6663 -8.334
Y : 0.0000 4.6293 4.629
Z : 0.0000 -5.8585 -5.858

Total Error : 11.189350

Marker:17 Label: IX

X : 0.0000 -4.9479 -4.948
Y : 0.0000 -1.9736 -1.974
Z : -668.0000 -664.4411 3.559

Total Error : 6.406417

Marker:18 Label: JX

X : 0.0000 5.7517 5.752
Y : 0.0000 5.7965 5.797
Z : -1337.0000 -1335.5257 1.474

Total Error : 8.297894

Marker:19 Label: KX

X : 0.0000 4.5799 4.580
Y : 2015.0000 2018.1078 3.108
Z : -672.0000 -674.9264 -2.926

Total Error : 6.260829

Marker:20 Label: LX

X : 0.0000 0.1843 0.184
Y : 2015.0000 2008.7103 -6.290
Z : -1343.0000 -1342.3477 0.652

Total Error : 6.326123

Marker:21 Label: MX

X : 2015.0000 2016.4453 1.445
Y : 2013.0000 2014.5956 1.596
Z : -672.0000 -669.2807 2.719

Total Error : 3.468339

Marker:22 Label: NX

X : 2015.0000 2010.2952 -4.705
Y : 2013.0000 2013.9935 0.994
Z : -1347.0000 -1343.7987 3.201

Total Error : 5.776789

Marker:23 Label: OX

X : 2015.0000 2016.2812 1.281
Y : 0.0000 -0.3521 -0.352
Z : -675.0000 -675.1118 -0.112

Total Error : 1.542774

Marker:24 Label: PX

X : 2015.0000 2018.1830 3.183
Y : 0.0000 2.7305 2.730
Z : -1344.0000 -1344.3222 -0.322

Total Error : 4.206067

Marker:25 Label : QX visible in less than 2 cameras.

Marker:26 Label : RX visible in less than 2 cameras.

Marker:27 Label: SX

X : 670.0000 669.7495 -0.251
Y : 2015.0000 2012.3694 -2.131
Z : -2015.0000 -2022.6450 -7.645

Total Error : 7.940293

Marker:28 Label: TX

X : 1342.0000 1335.9945 -6.005
Y : 2015.0000 2010.7130 -4.287
Z : -2019.0000 -2021.6495 -2.649

Total Error : 7.339854

Marker:29 Label : UX visible in less than 2 cameras.

Marker:30 Label : VX visible in less than 2 cameras.

Marker:31 Label: WX

X : 1340.0000 1349.3420 9.342
Y : 0.0000 3.3668 3.367
Z : -2013.0000 -2015.9763 -2.976

Total Error : 10.366644

Marker:32 Label : XX visible in less than 2 cameras.

Absolute Mean Error : 8.037193

APPENDIX C

SUBJECT INFORMATION PACKAGE

AND CONSENT FORM

1. Subject Information Package

A) PROJECT TITLE

A Three Dimensional Kinematic Analysis of Alpine Skiing in Moguls.

B) PROJECT OBJECTIVES

In order to better understand the kinematics of mogul skiing the specific aims of the project are to:

1. develop normative data for three dimensional motion of skilled skiers when turning on a mogul,
2. determine differences in this motion between the samples of competitive skiers and instructors,
3. establish if either technique is more likely to cause injury at the knee joint.

C) TEST PROCEDURES

For the study you will be required to complete a typical run down a mogul ski field. You will be familiar with the position of one 'reference mogul' on which you are required to complete one turn. This specific turn will be filmed for later analysis. You will be required to complete this procedure three times.

D) RISKS AND DISCOMFORTS

As the study involves a typical ski run there is no more risk involved than at any other time when skiing moguls. However a medical practitioner will be present at all times during testing in case of injury.

E) INQUIRIES

Questions concerning the procedures and/or rationale used in this investigation are welcome at any time. Please ask for clarification of any point which you feel is not explained to your satisfaction. Your initial contact person is the investigator conducting this project; Anton Arndt (Department of Human Movement Science, University of Wollongong). Subsequent inquiries may be directed to Prof. A.W. Parker (Head of Department of Human Movement Science: phone 213881).

F) FREEDOM OF CONSENT

Participation in this project is entirely voluntary. You are free to deny consent before or during the experiment. In the latter case such withdrawal of consent should be performed at the time you specify, and not at the end of a particular trial. Your participation and/or withdrawal of consent will not influence your present and/or future involvement with the University of Wollongong. In case of student involvement, it will not influence grades awarded by the University. You have the right to withdraw from any experiment, and this right shall be preserved over and above the goals of the experiment.

G) CONFIDENTIALITY

All questions, answers and results of this study will be treated with absolute confidentiality. Subjects will be identified in the resultant manuscripts, reports or publications by the use of subject codes only.

2. Subject Consent Form

INFORMED CONSENT FORMA THREE DIMENSIONAL KINEMATIC ANALYSIS OF ALPINE SKIING IN MOGULS

The researchers conducting this project support the principles governing both the ethical conduct of research, and the protection at all times of the interests, comfort and safety of subjects.

This form and the accompanying Subject Information Package are given to you for your own protection. They contain a detailed outline of the experimental procedures, and possible risks. Your signature below indicates six things:

1. you have received the Subject Information Package;
2. you have read its contents;
3. you have been given the opportunity to discuss the contents with one of the researchers prior to commencing the experiment;
4. you clearly understand these procedures and possible risks;
5. you voluntarily agree to participate in the project; and
6. your participation may be terminated at any point in time without jeopardizing your involvement with the University of Wollongong, or your assessment for this or any other course undertaken through the University.

Any concerns or further questions may be directed initially to Anton Arndt (c/- Department of Human Movement Science: Phone 213881). Any complaints regarding the conduct of this research may be directed to the Secretary of the University of Wollongong Human Experimentation Ethics Committee on (042) 213-079).

I am an experienced mogul skier. I freely and voluntarily agree to participate as a subject in the study titled "A Three Dimensional Kinematic Analysis of Alpine Skiing in Moguls".

Last name: _____ Given name: _____

Date of Birth: __/__/__ Phone: _____

Address: _____

Signature: _____ Date: __/__/__

Witness Name: _____ Signature: _____

Name and phone number of contact person in case of an emergency:

Name: _____ Phone: _____

APPENDIX D

POSITIONS OF THE SUBJECT MARKERS

Foot:

Subject 1.

If1: Superior aspect of centre of anterior margin of ski boot; approximating second distal phalange,

If2: Lateral aspect of widest section of boot; approximating head of fifth metatarsal,

If3: Superior ridge of second lateral buckle of ski boot; approximating antero-lateral aspect of cuboid.

Subject 2.

If1: Anterior aspect of most anterior point of ski boot; approximating anterior aspect of second distal phalange,

If2: Superior aspect of mid ridge of ski boot; approximating mid shaft of third metatarsal,

If3: As for Subject 1.

Subject 3.

If1: Antero-medial aspect of mid medial margin of ski boot; approximating mid shaft of first metatarsal,

If2: 5 cm proximal to If1; approximating base of first metatarsal,

If3: As for Subject 1.

Left Leg:

Subject 1.

Il1: On peroneus longus, midway between head of fibula and lateral malleolus,

Il2: On tibialis anterior, lateral aspect, mid muscle,

Il3: Anterior aspect of tibial tuberosity.

Subject 2.

ll1: Anterior aspect of tibia midway between medial malleolus and tibial tuberosity,

ll2: On peroneus longus, midway between head of fibula and lateral malleolus,

ll3: Lateral aspect of head of fibula.

Subject 3.

As for Subject 1.

Left Thigh:

Subject 1.

lt1: Anterio-superior aspect of base of patella,

lt2: On biceps femoris, midway between ischial tuberosity and head of fibula,

lt3: Lateral aspect of greater trochanter of the femur.

Subject 2.

lt1: As for Subject 1,

lt2: Anterio-medial aspect of vastus lateralis, 10 cm inferior to greater trochanter of femur,

lt3: As for Subject 1.

Subject 3.

As for Subject 1.

Right Leg:

Subject 1.

rl1: On anterior aspect of superior rim of ski boot; approximating anterior aspect of tibia 15 cm superior to medial malleolus,

rl2: Anterio-medial aspect of tibia midway between medial malleolus and tibial tuberosity,

rl3: Anterior aspect of tibial tuberosity.

Subject 2.

rl1: Anterior aspect of mid upper ski boot; approximating anterior aspect of tibia 5 cm superior to talus,

rl2: On anterior aspect of superior rim of ski boot; approximating anterior aspect of tibia 15 cm superior to medial malleolus,

rl3: Anterio-medial aspect of tibia midway between medial malleolus and tibial tuberosity.

Subject 3.

rl1: As for Subject 1.

rl2: As for Subject 1.

rl3: Anterio-lateral aspect of head of fibula.

Right Thigh:

Subject 1:

rt1: Anterior aspect of lateral epicondyle of femur,

rt2: Mid sartorius muscle,

rt3: 5 cm inferior to groin line, on adductor longus.

Subject 2.

rt1: As for Subject 1.

rt2: Vastus medialis, 15 cm superior to base of patella,

rt3: Vastus lateralis, 20 cm inferior to greater trochanter of femur.

Subject 3.

rt1: Anterior aspect of tendon of quadriceps femoris, 5 cm superior to base of patella,

rt2: Vastus lateralis, 20 cm inferior to greater trochanter of femur,

rt3: As for Subject 1.

Torso:

Subject 1.

- t1: Anterior margin of right anterior superior iliac spine,
- t2: Anterior margin of left anterior superior iliac spine,
- t3: Anterio-lateral margin of costal angle of 10th rib on left side,
- t4: Lobule of left ear (no marker attached).

Subject 2.

- t1: Anterior margin of left anterior superior iliac spine,
- t2: Anterio-lateral margin of costal angle of 10th rib on left side,
- t3: Anterior aspect of mid xyphoid process,
- t4: As for Subject 1.

Subject 3.

As for Subject 1.

APPENDIX E

TRANSFORMATION MEASUREMENTS

1. Subject 1 Final Transformation Measurements

	X (mm)	Y (mm)	Z (mm)	length (mm)
<i>lf1</i>	42	271	74	270
<i>lf2</i>	-14	260	7	270
<i>lf3</i>	78	159	12	270
<i>ll1</i>	334	-56	87	513
<i>ll2</i>	203	0	88	513
<i>ll3</i>	67	68	-2	513
<i>lt1</i>	493	101	0	520
<i>lt2</i>	274	-28	102	520
<i>lt3</i>	0	0	113	520
<i>rl1</i>	265	73	-10	499
<i>rl2</i>	186	49	33	499
<i>rl3</i>	75	51	-5	499
<i>rt1</i>	475	-12	-69	505
<i>rt2</i>	273	113	-50	505
<i>rt3</i>	165	122	14	505
<i>t1</i>	105	65	-181	714
<i>t2</i>	91	85	166	714
<i>t3</i>	307	120	116	714
<i>t4</i>	174	42	102	268

2. Subject 2 Final Transformation Measurements

	X (mm)	Y (mm)	Z (mm)	length (mm)
<i>lf1</i>	0	271	0	271
<i>lf2</i>	76	133	8	271
<i>lf3</i>	6	88	61	271
<i>ll1</i>	144	56	49	495
<i>ll2</i>	75	18	73	495
<i>ll3</i>	4	7	66	495
<i>lt1</i>	317	90	9	499
<i>lt2</i>	236	-64	93	499
<i>lt3</i>	2	0	115	499
<i>rl1</i>	258	79	-19	498
<i>rl2</i>	107	49	14	498
<i>rl3</i>	20	0	73	498
<i>rt1</i>	420	0	-95	503
<i>rt2</i>	311	93	6	503
<i>rt3</i>	186	64	-103	503
<i>t1</i>	125	75	136	712
<i>t2</i>	329	104	100	712
<i>t3</i>	371	124	-13	712
<i>t4</i>	152	35	91	248

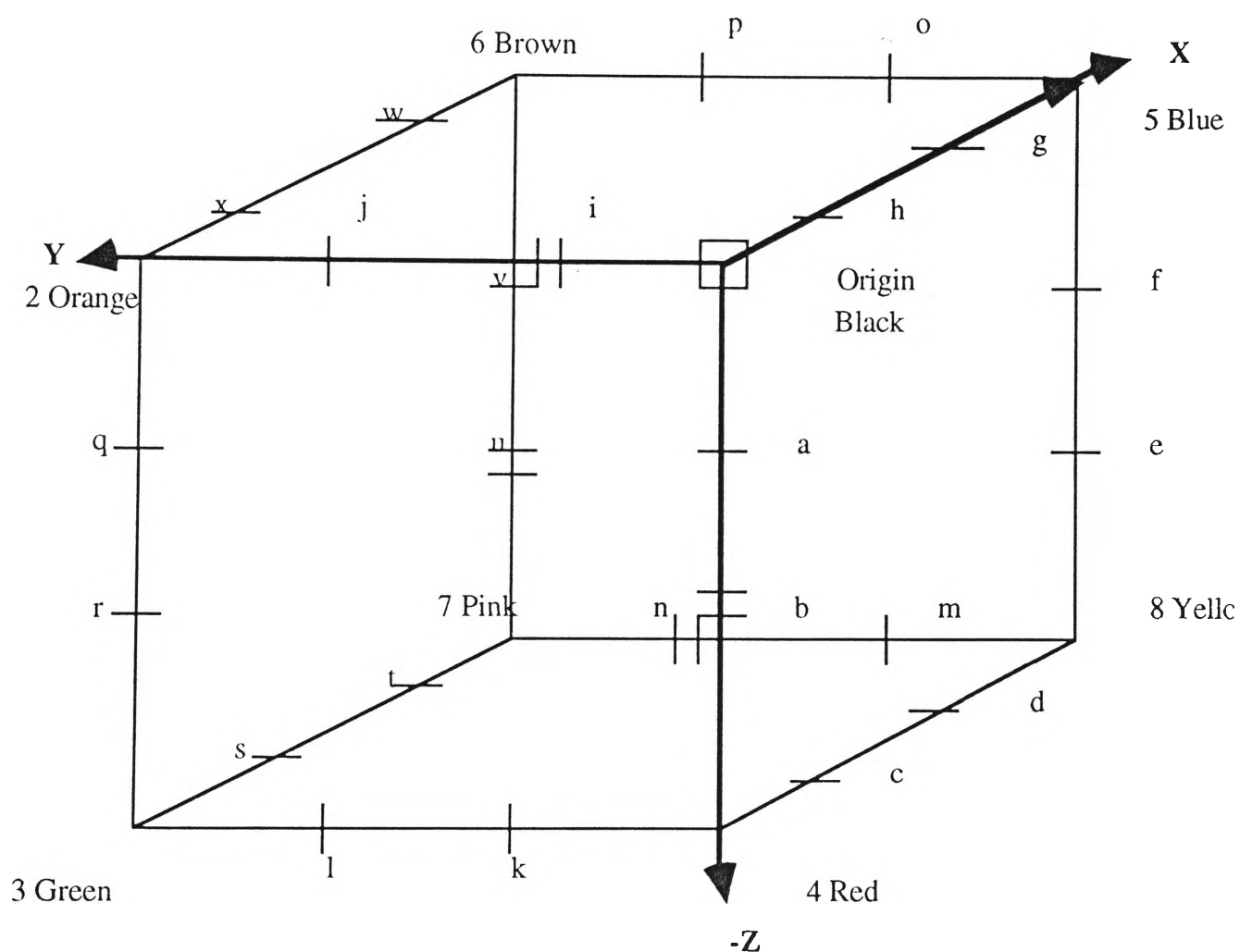
3. Subject 3 Final Transformation Measurements

	X (mm)	Y (mm)	Z (mm)	length (mm)
<i>lf1</i>	68	165	-48	262
<i>lf2</i>	85	123	-24	262
<i>lf3</i>	5	75	44	262
<i>ll1</i>	324	-114	61	508
<i>ll2</i>	196	-48	86	508
<i>ll3</i>	56	50	2	508
<i>lt1</i>	480	86	-17	514
<i>lt2</i>	263	-34	103	514
<i>lt3</i>	7	3	108	514
<i>rl1</i>	159	66	15	502
<i>rl2</i>	61	76	-13	502
<i>rl3</i>	23	0	-77	502
<i>rt1</i>	382	139	-12	514
<i>rt2</i>	270	156	-45	514
<i>rt3</i>	307	148	16	514
<i>t1</i>	121	109	-173	671
<i>t2</i>	77	108	164	671
<i>t3</i>	286	122	122	671
<i>t4</i>	160	-11	89	288

APPENDIX F

CALIBRATION CUBE COORDINATES

1. Relation between the Global Axes and the Colour Coding of the Cube



2. Distances of Control Points in X, Y, and Z Directions from Origin :

		X(m)	Y(m)	Z(m)
Origin, Black	1	0	0	0
	2	0	0	-2.015
	3	0	2.015	-2.015
	4	0	2.015	0
	5	2.015	0	0
	6	2.018	0	-2.013
	7	2.015	2.010	-2.019
	8	2.015	2.013	0
Blue face				
	a	0	0.675	0
	b	0	1.344	0
	c	0.676	2.015	0
	d	1.340	2.015	0
	e	2.015	1.344	0
	f	2.015	0.669	0
	g	1.343	0	0
	h	0.679	0	0
Red face				
	i	0	0	-0.668
	j	0	0	-1.337
	k	0	2.015	-0.672
	l	0	2.015	-1.343
	m	2.015	2.013	-0.672
	n	2.015	2.013	-1.347
	o	2.015	0	-0.675
	p	2.015	0	-1.344
Green face				
	q	0	0.672	-2.015
	r	0	1.337	-2.015
	s	0.670	2.015	-2.015
	t	1.342	2.015	-2.019
	u	2.015	1.346	-2.019
	v	2.018	0.679	-2.013
	w	1.340	0	-2.013
	x	0.675	0	-2.015

APPENDIX G

AN OVERVIEW OF ALL TRIALS

1. Summary by Visual Analysis of Film of Major Events (Seconds after Beginning of Trial) :

Trial	Max. Extension	Lands 1	Impact	Leaves Ground	Lands 2
S1T1	0.085	no air	0.185	0.290	no
S1T2	0.050	no air	0.155	0.265	no
S1T3	0.055	0.055	0.145	0.275	0.450
S1T4	0.025	0.025	0.155	0.270	no
S2T1	0.025	past	0.125	0.260	no
S2T2	past	past	0.085	0.195	no
S2T3	0.145	0.145	0.145	0.290	no
S2T4	0.005	past	0.090	0.280	no
S3T1	0.020	no air	0.130	0.315	no
S3T2	0.050	no air	0.110	0.255	no
S3T3	0.045	0.045	0.075	0.195	no
S3T4	0.035	0.035	0.100	0.195	no

Where :

Max. Extension = the frame of maximal knee extension,

Lands 1. = the frame in which the subject lands after pre-reference mogul,

Impact = the frame in which the ski under the base of boot makes contact with the reference mogul,

Leaves Ground = the frame in which the ski under the base of boot loses contact with the surface of the reference mogul,

Lands 2. = the frame in which the subject lands after the reference mogul,

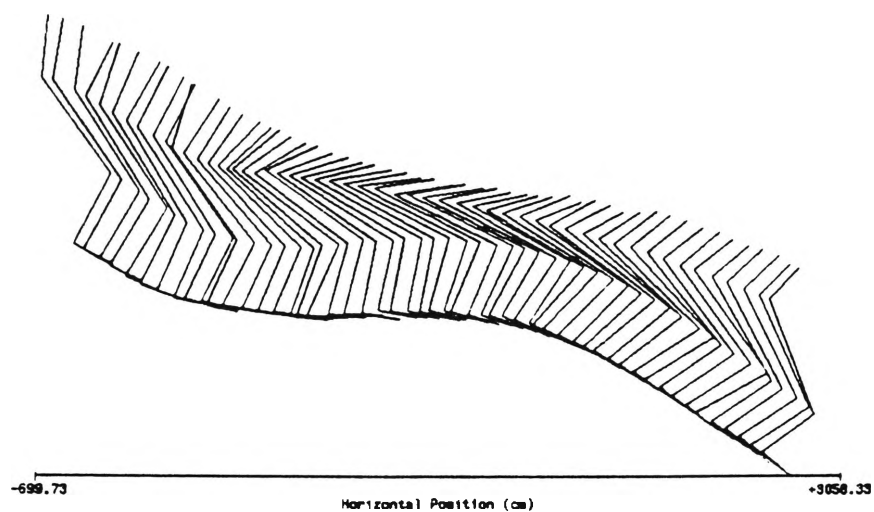
past = the event has already occurred,

no = the event has not occurred, and

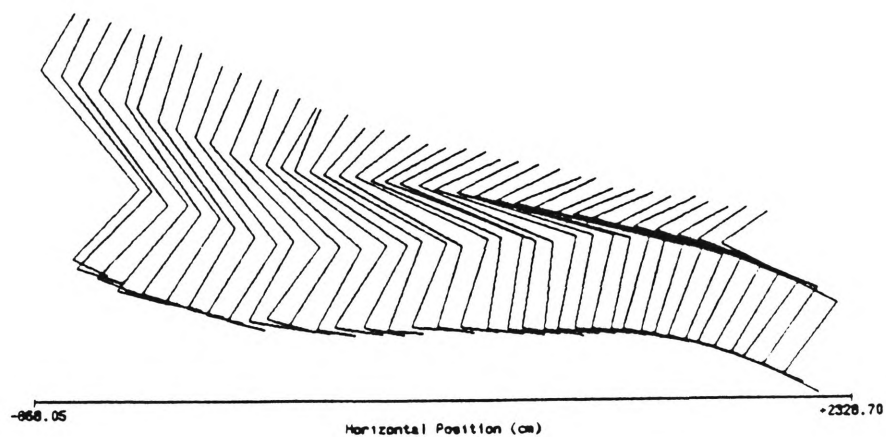
no air = the skis did not lose contact with the snow after the pre-reference mogul.

2. Stick Figure Representations of all Trials in xz View.

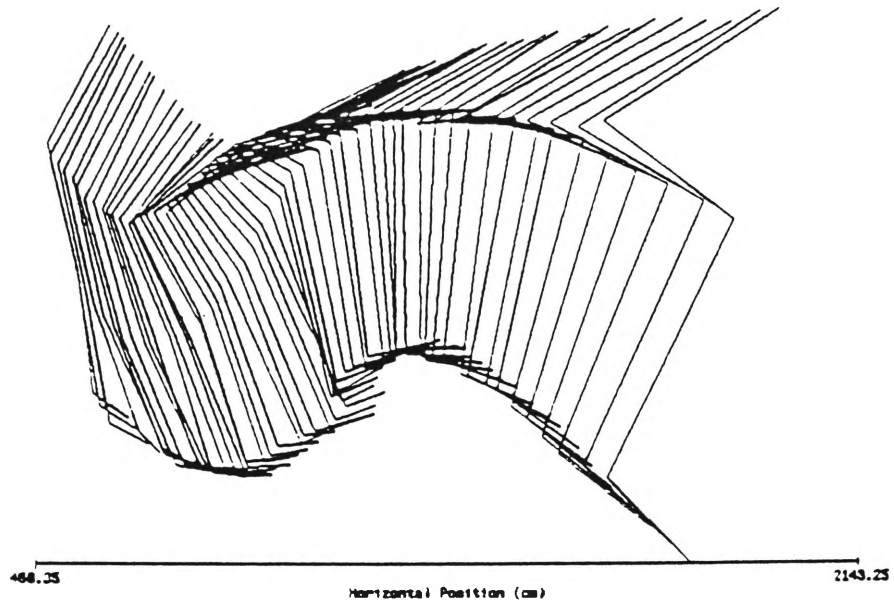
File: sit3.ted
Display Range:
First Frame: 1
Last Frame: 105
Frame Increment: 2
View Plane: xz



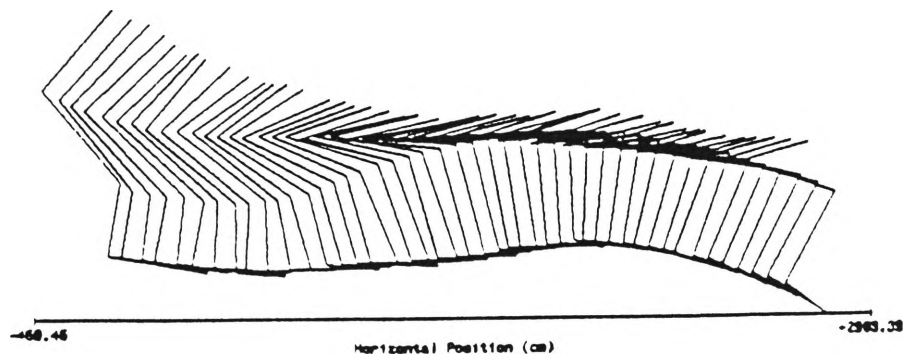
File: sit4.ted
Display Range:
First Frame: 1
Last Frame: 75
Frame Increment: 2
View Plane: xz



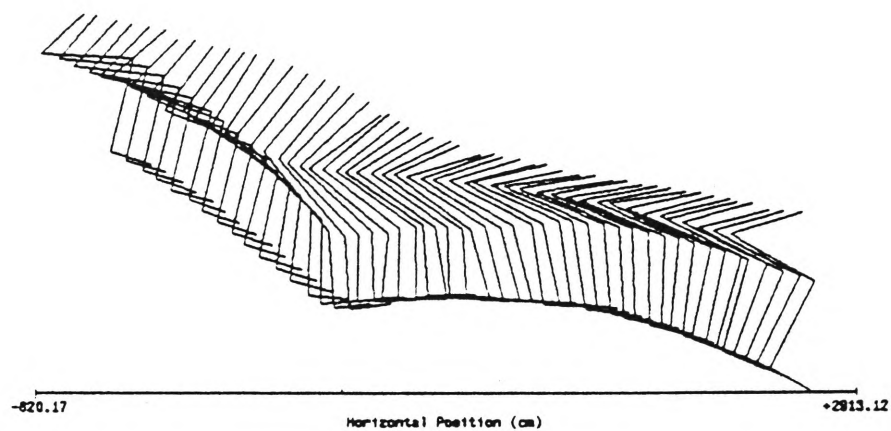
File: a211.tad
Display Range:
First Frame: 1
Last Frame: 105
Frame Increment: 2
View Plane: xz



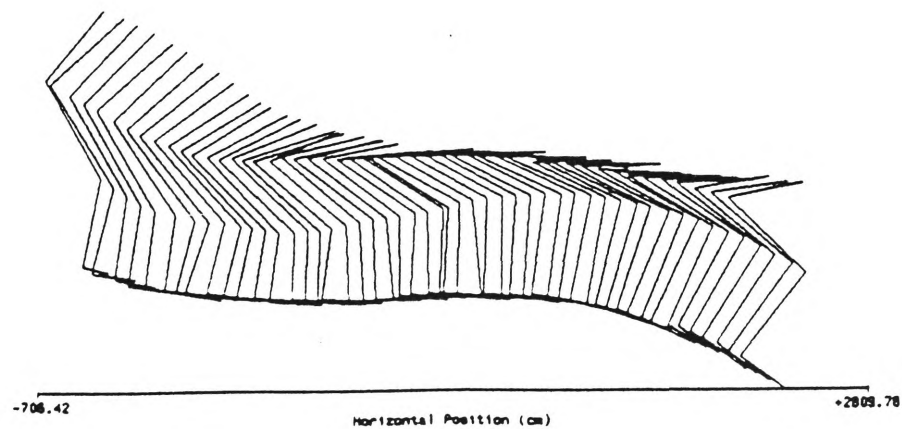
File: a212.tad
Display Range:
First Frame: 1
Last Frame: 98
Frame Increment: 2
View Plane: xz



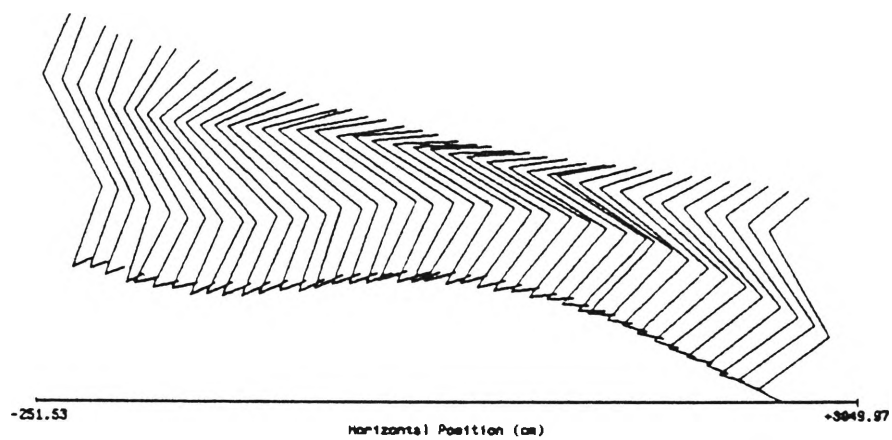
File: s213.tad
Display Range:
First Frame: 1
Last Frame: 100
Frame Increment: 1
View Plane: xz



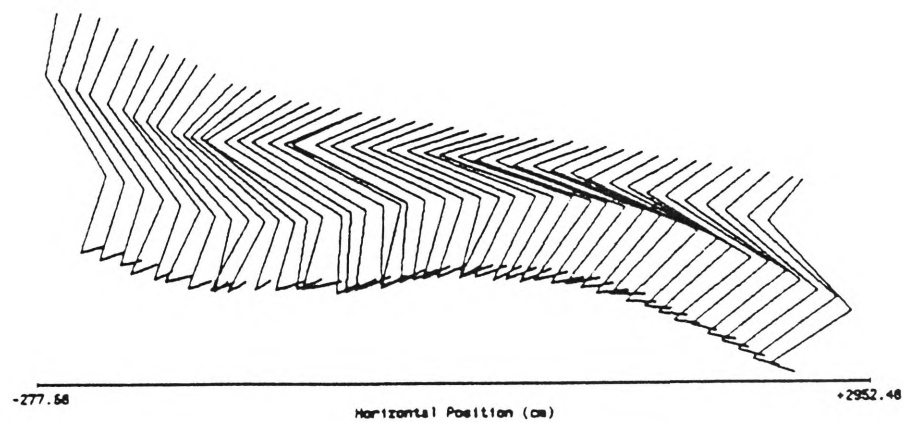
File: s214.tad
Display Range:
First Frame: 1
Last Frame: 100
Frame Increment: 2
View Plane: xz



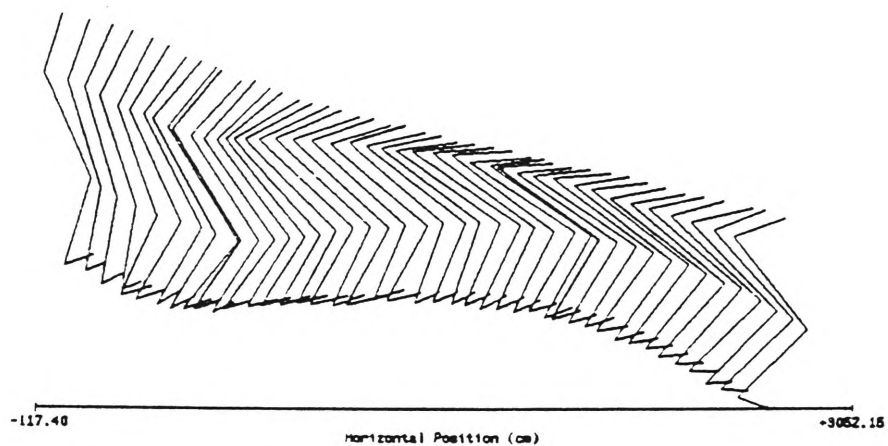
File: s3t1.ted
Display Range:
First Frame: 1
Last Frame: 83
Frame Increment: 2
View Plane: xz



File: s3t2.ted
Display Range:
First Frame: 1
Last Frame: 90
Frame Increment: 2
View Plane: xz



File: s3t3.ted
Display Range:
First Frame: 1
Last Frame: 85
Frame Increment: 2
View Plane: xz



File: s3t4.ted
Display Range:
First Frame: 1
Last Frame: 85
Frame Increment: 2
View Plane: xz

